Winds of change in wave-like dark matter

Rising Stars Symposium

Chelsea Bartram

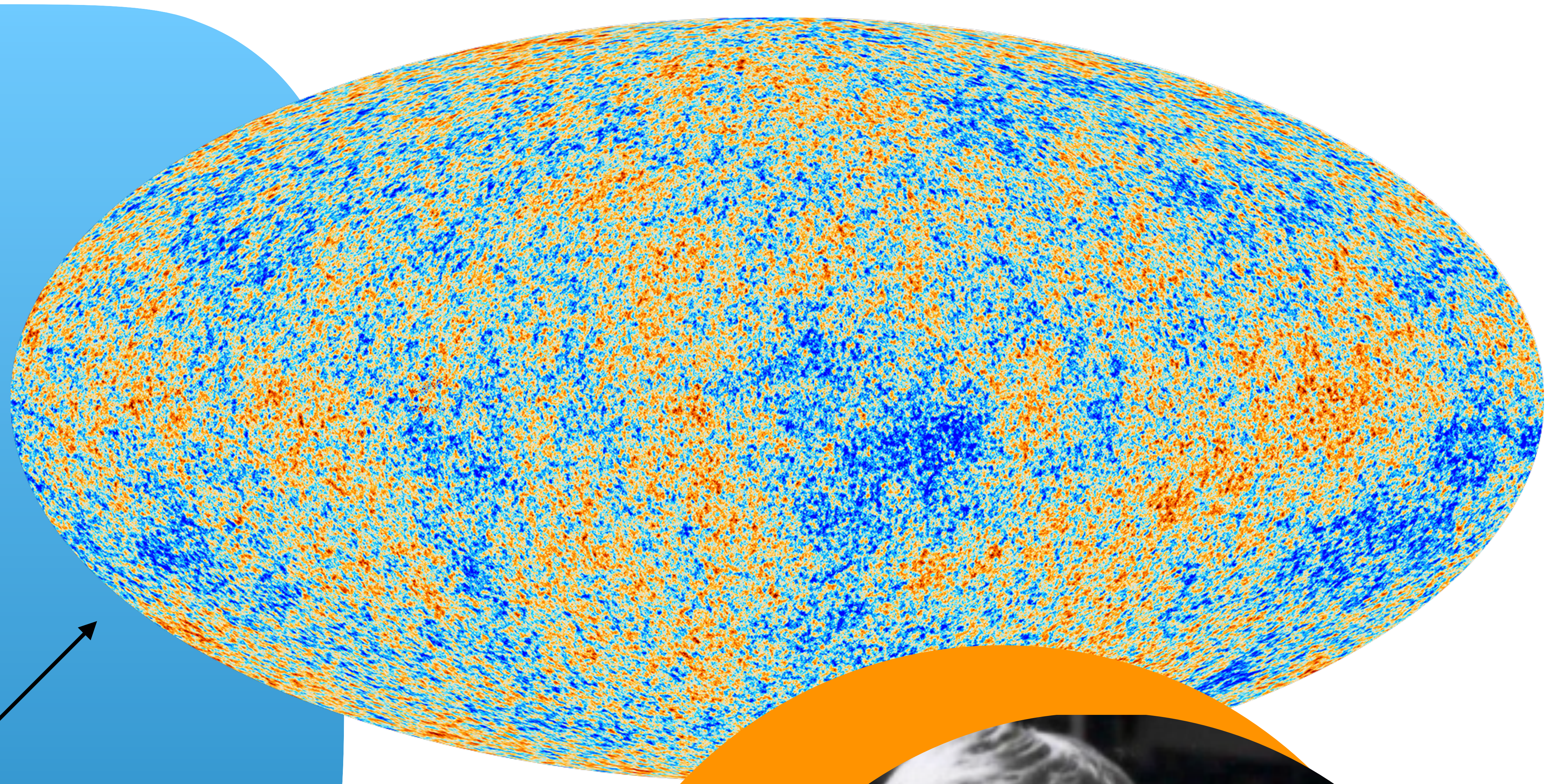
UNIVERSITY OF WASHINGTON · LVX · SIT · 1861

ADMX
AXION DARK MATTER EXPERIMENT

What is dark matter?

'Invisible' matter that would be able to explain:

- Anisotropies in the cosmic microwave background
- Rotation curves of galaxies
- Behavior of galaxy cluster collisions
- Matter Radiation Fluctuations
- Primordial nucleosynthesis
- Gravitational lensing
- Baryon Acoustic Oscillations



ESA and the Planck Collaboration

Characteristics of the dark matter:

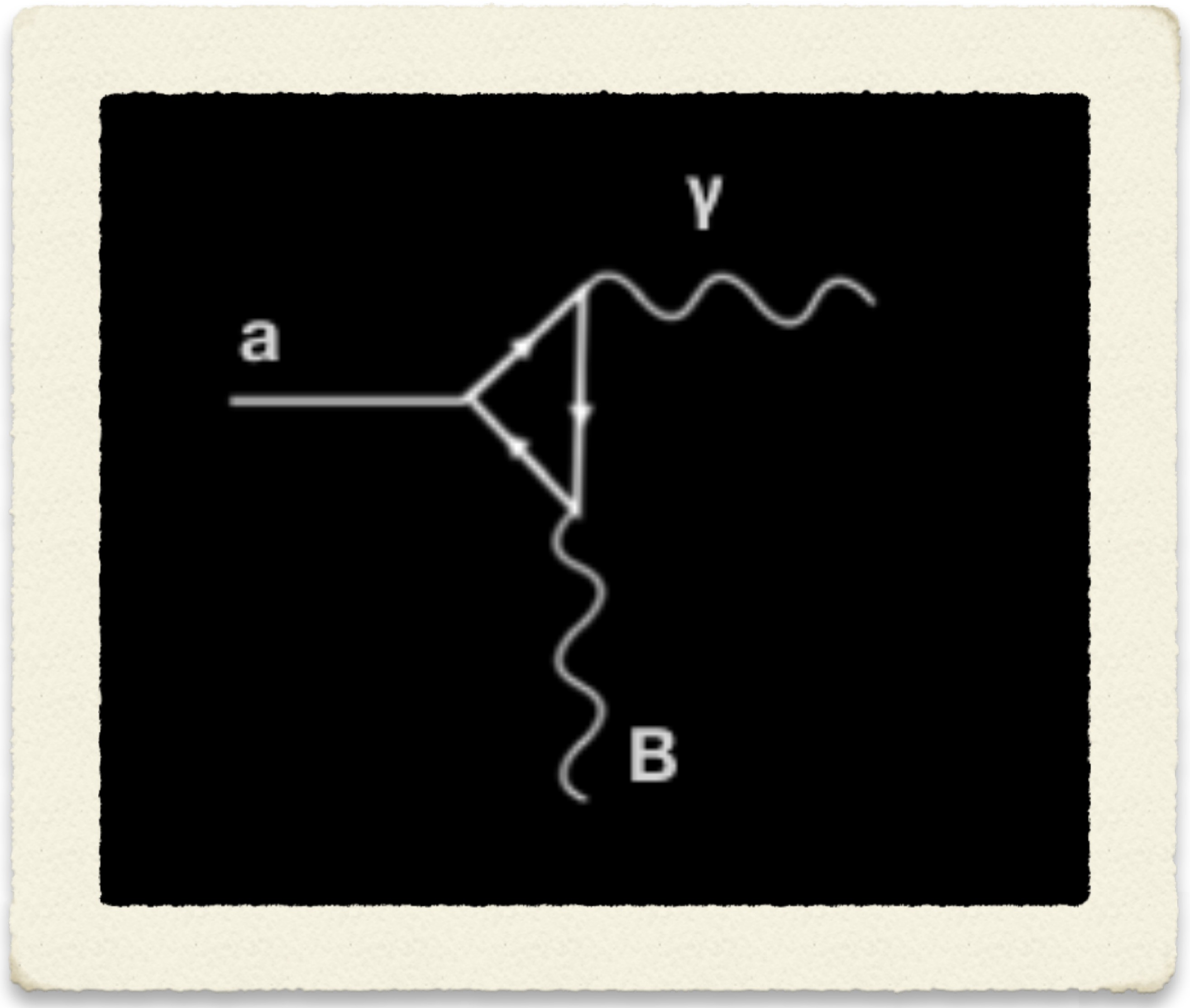
- Cold (non-relativistic)
- Feebly-interacting
- Non-baryonic
- Gravitationally-interacting
- Very stable

Vera Rubin

Axions as Dark Matter

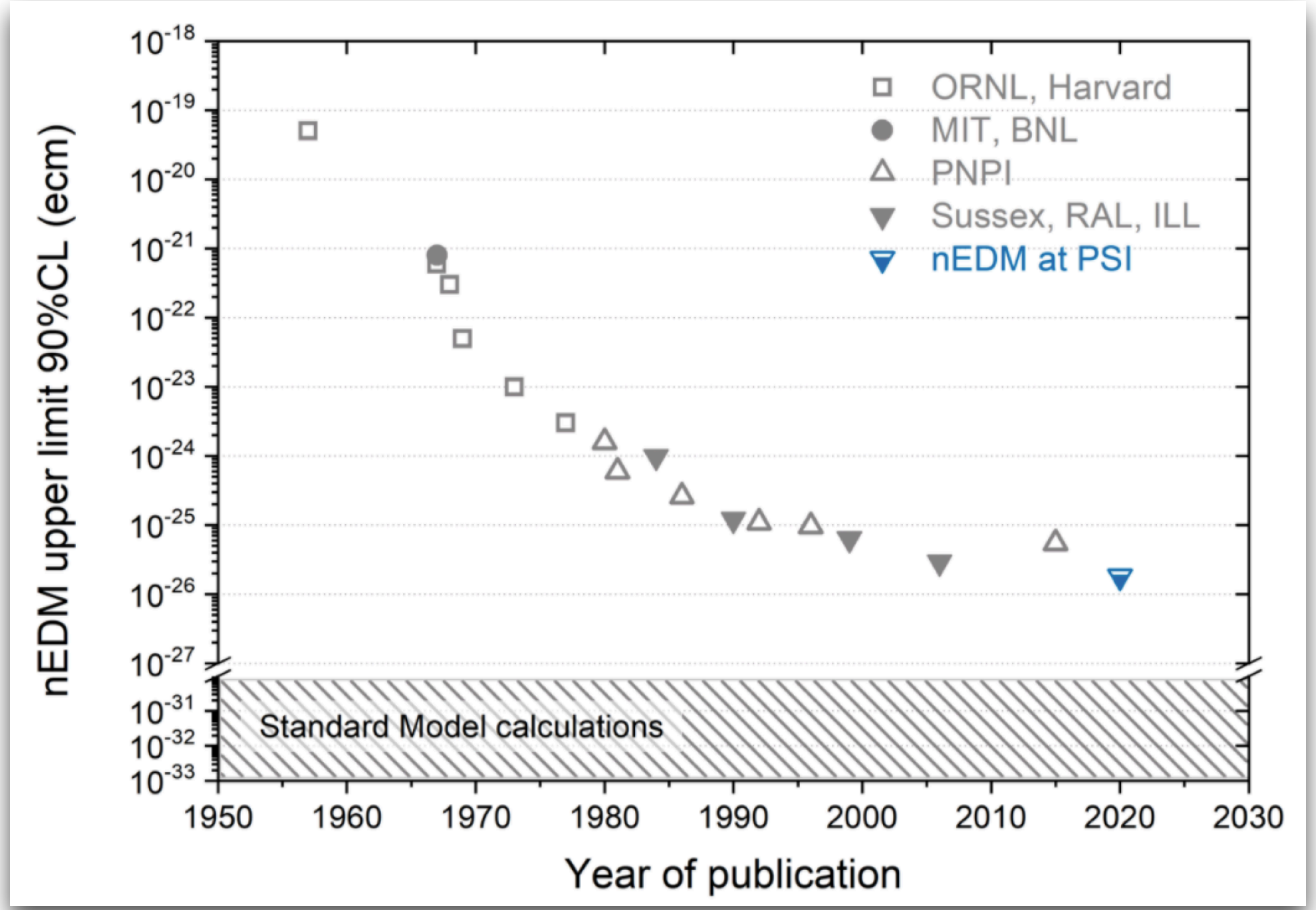
- 1-100 μeV mass range to constitute entirety of dark matter

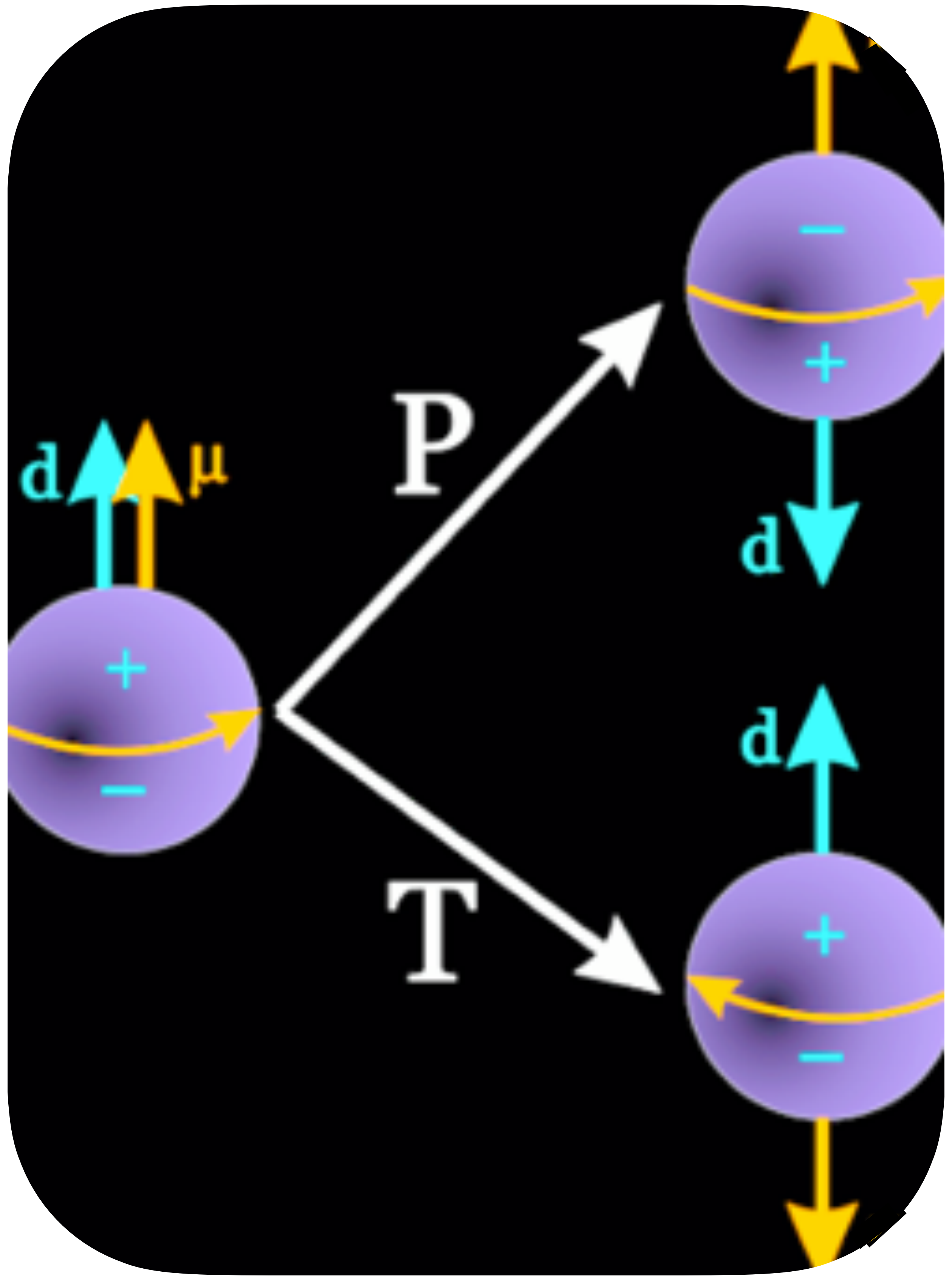
- Two classes of models:
  - **KSVZ (Kim-Shifman-Vainshtein-Zakharov)**:
    - couples to leptons
    - Range of g_γ values, typically g_γ=-0.97 used
  - **DFSZ (Dine-Fischler-Srednicki-Zhitnitsky):**
    - couples to quarks and leptons
    - Range of g_γ values, typically g_γ=0.36 used



strong CP problem

Neutron electric dipole moment





EDM would violate T (CP) symmetry

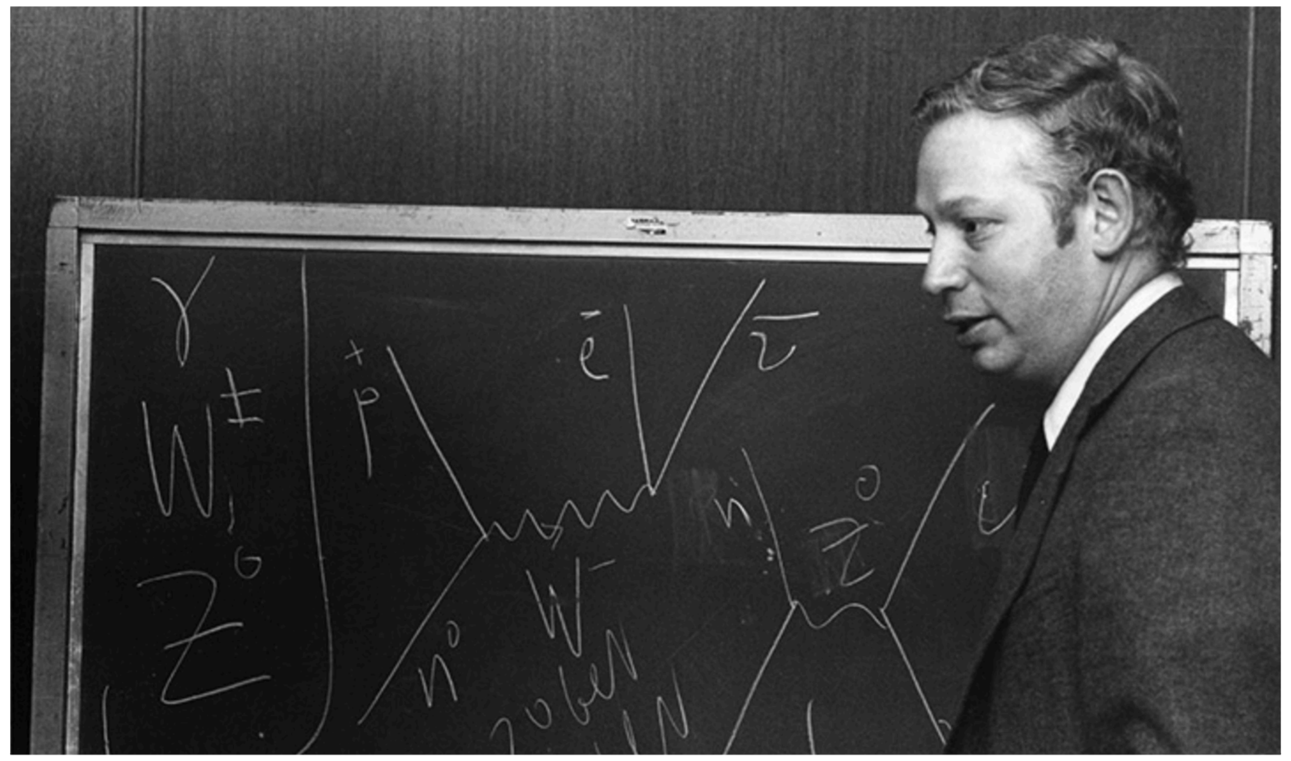
Peccei-Quinn Mechanism

- Peccei-Quinn devised solution that upgraded theta to dynamical variable
- Tips the wine-bottle potential so that lowest energy configuration precludes existence of neutron EDM
- ‘PQ’ mechanism —> pseudo scalar boson (axion)

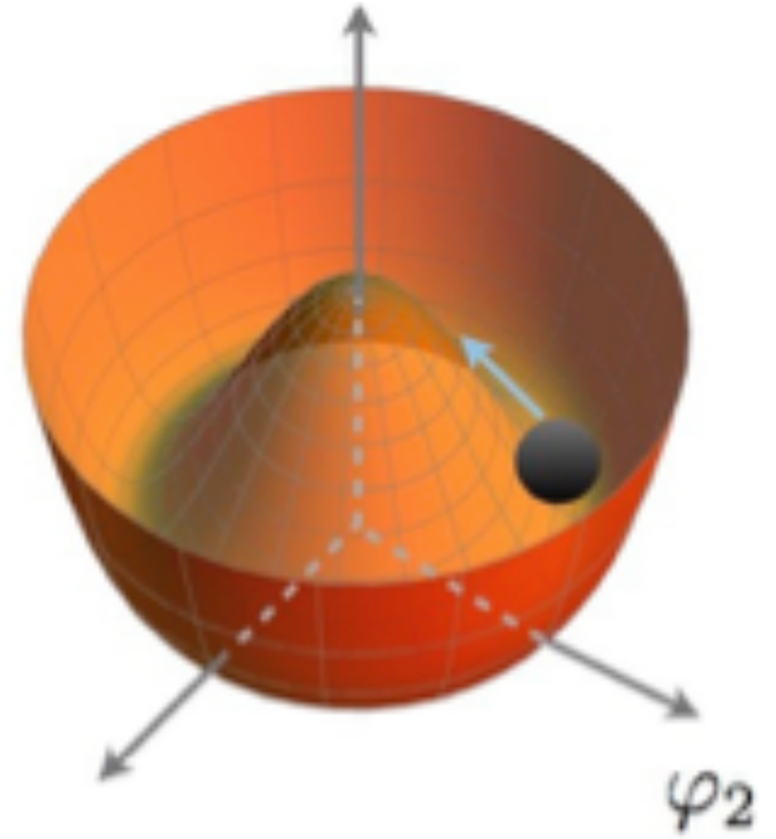
Frank Wilçek

Helen Quinn

Roberto Peccei
1942-2020

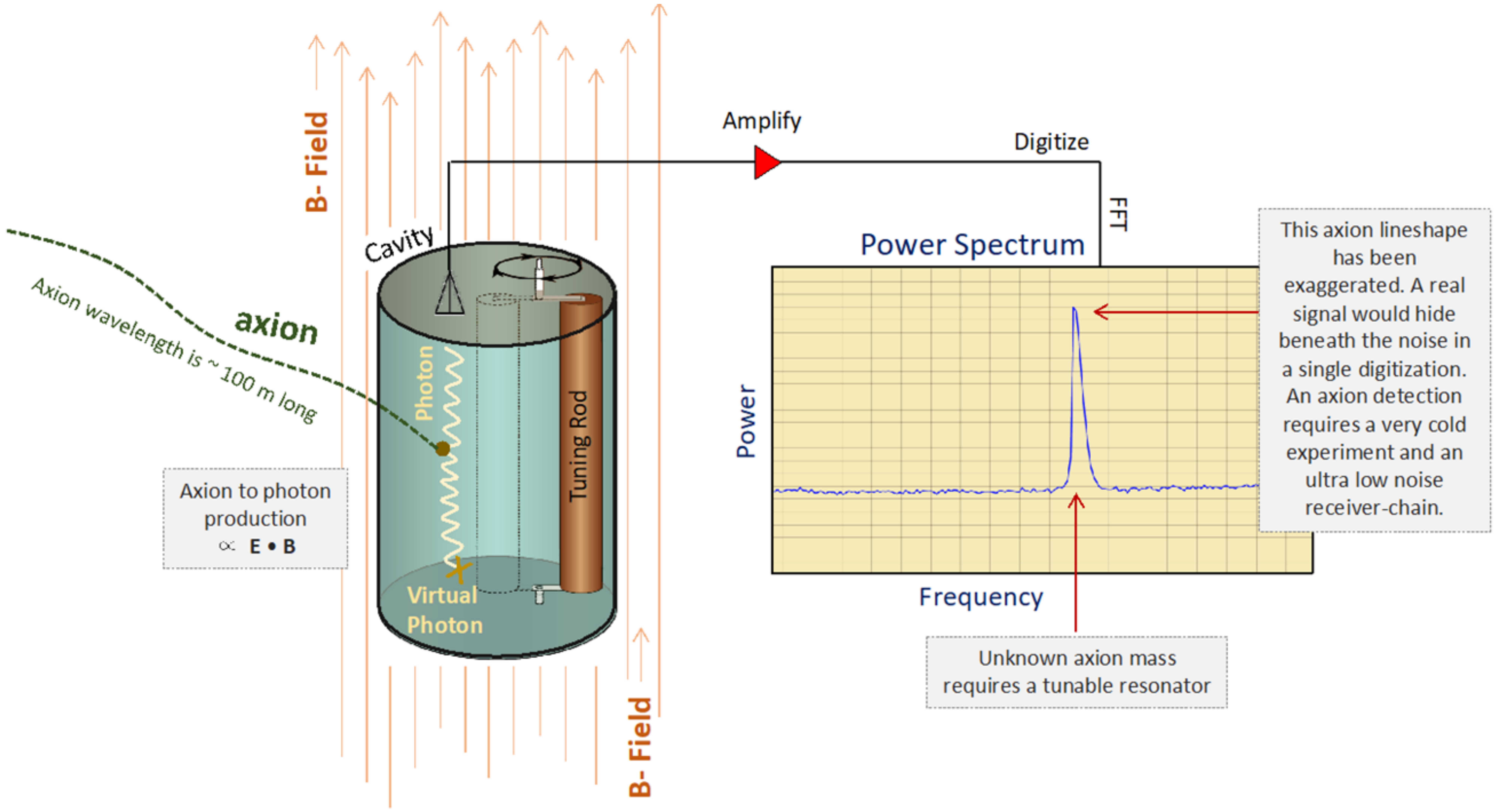


Steven Weinberg (1933-2021)



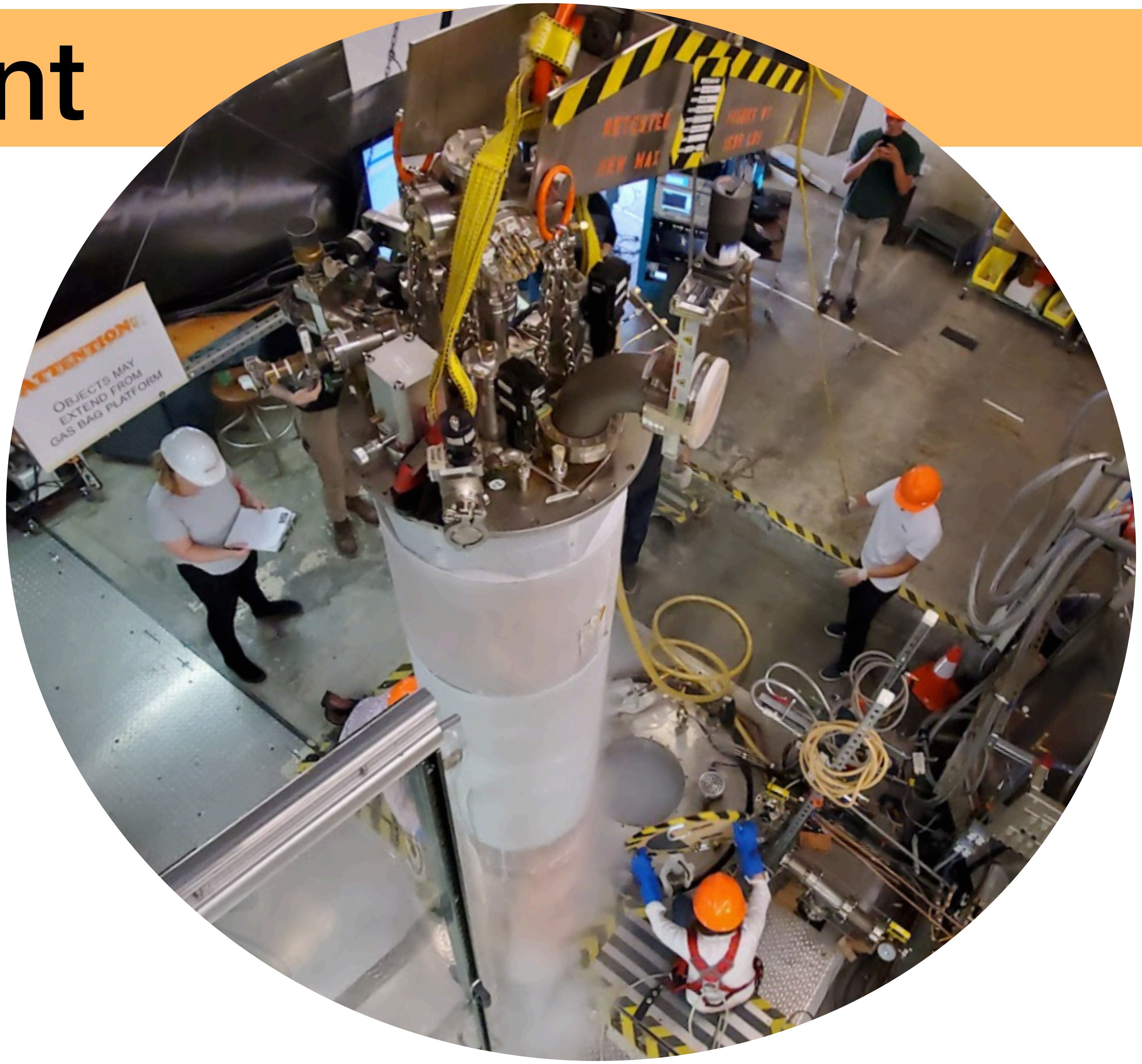
Oscillation about the QCD minimum – *Daniel Grin*

The Axion Haloscope



Axion Dark Matter eXperiment

- Resonant cavity in a magnetic field (‘haloscope’)
- Relying on inverse Primakoff effect
- High-Q —> Higher probability of axion to photon conversion
- Have reached DFSZ benchmark sensitivity with the ADMX detector



Berkeley UNIVERSITY OF CALIFORNIA

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

University of Washington 1861

THE UNIVERSITY OF WESTERN AUSTRALIA

Washington University in St. Louis 1853

Pacific Northwest NATIONAL LABORATORY

Lawrence Livermore National Laboratory

UF UNIVERSITY of FLORIDA

The University Of Sheffield.

Fermilab

Los Alamos NATIONAL LABORATORY

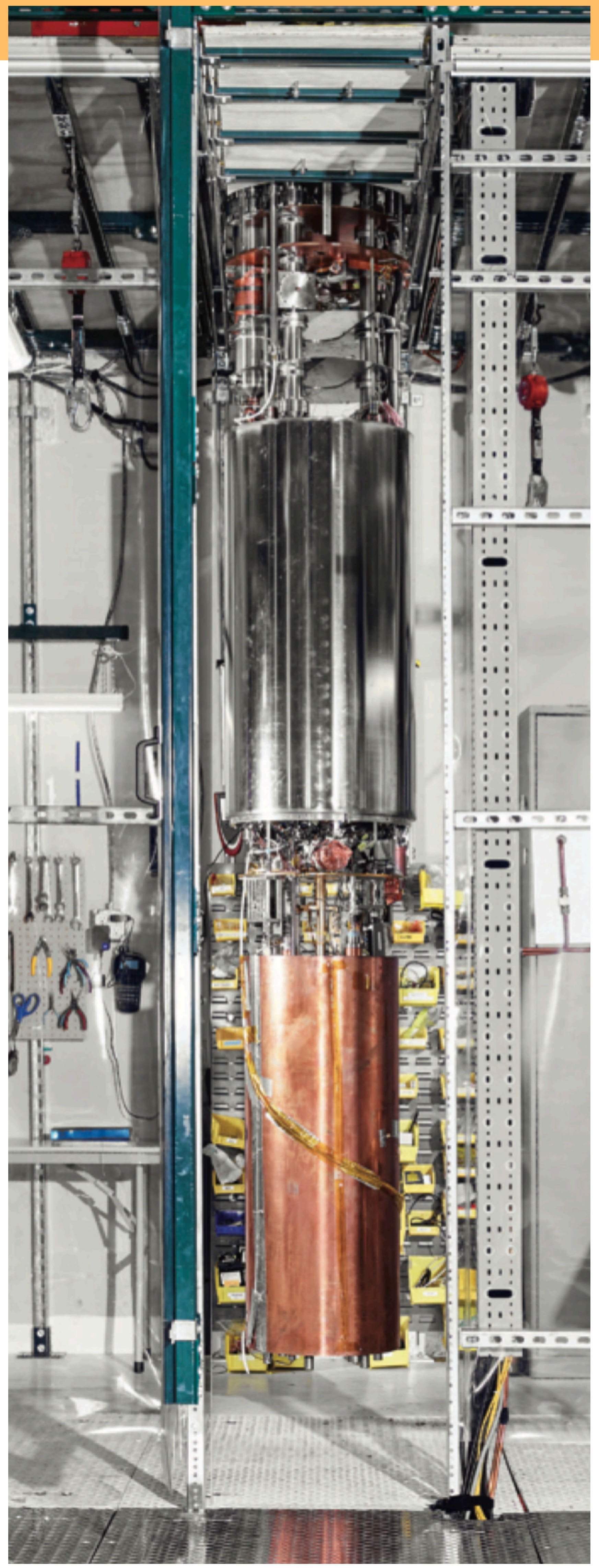
United States Department of Energy

NSF

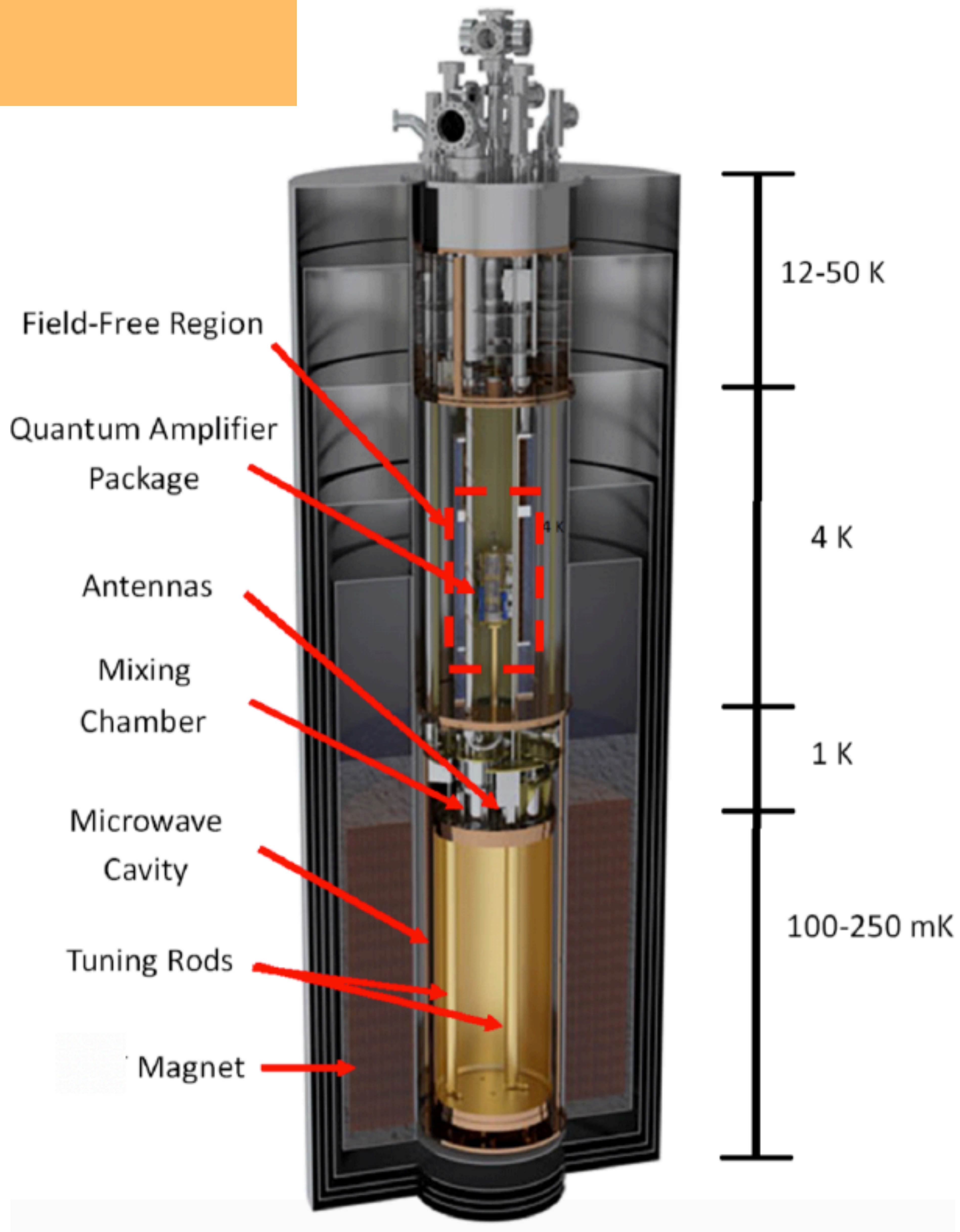
HEISING - SIMONS FOUNDATION

ADMX

- Dil Fridge: Reaches ~100 mK
- Superconducting magnet:
  ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics



In cleanroom



In magnet bore

Data-taking operations 2019-2021

Medium-res

- 100 Hz bin width
- Saved as power spectra
- Isothermal halo model
- Bin width optimized for expected axion lineshape

High-res

- 10 mHz native bin width
- Saved as time-series
- Non-virialized axions
- Sensitive to frequency modulation from orbital and rotational motion

Data-taking operations 2019-2021

Medium-res

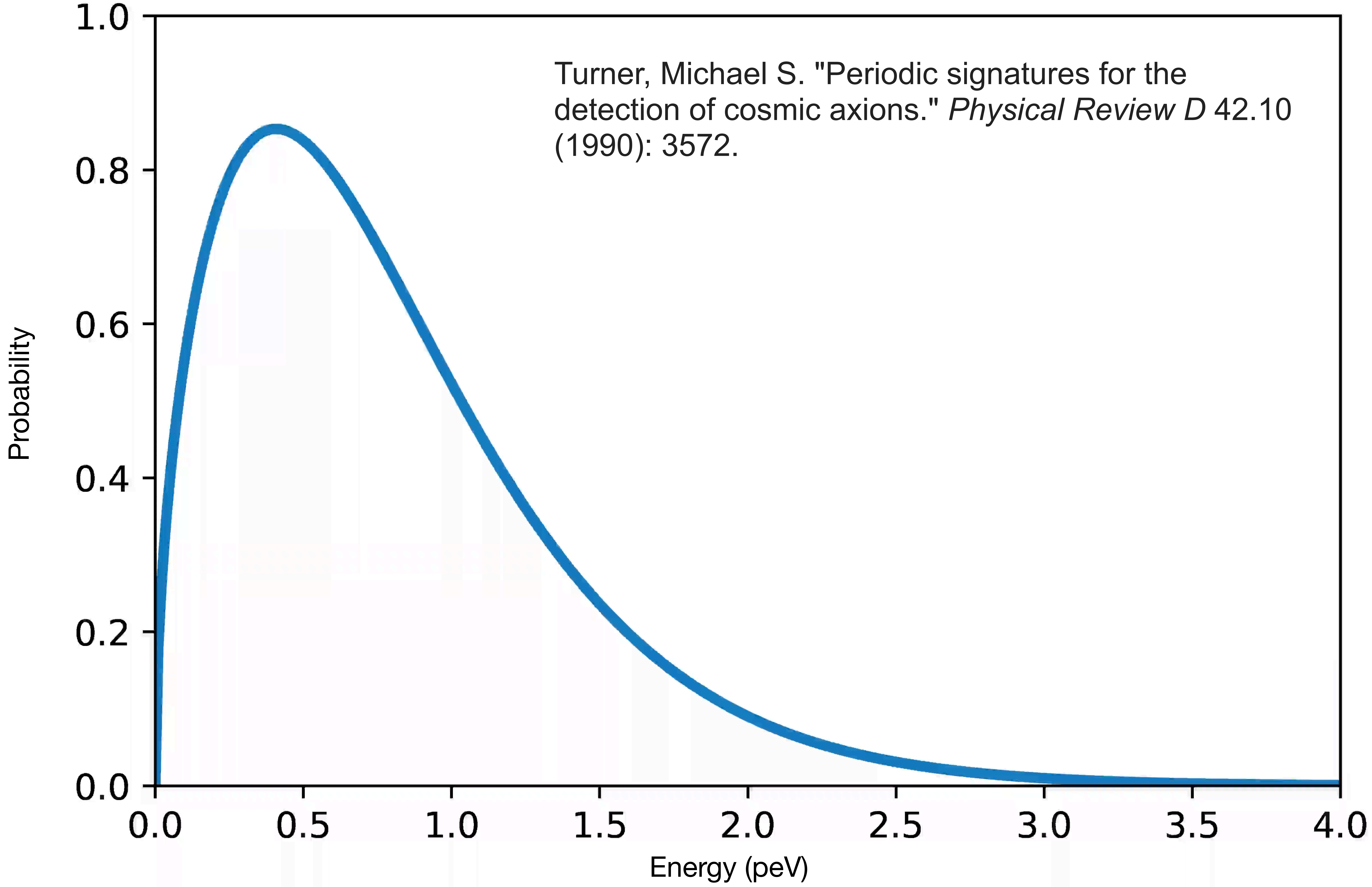
Driving the data-taking operations!

- 100 Hz bin width
- Saved as power spectra
- Isothermal halo model
- Bin width optimized for expected axion lineshape

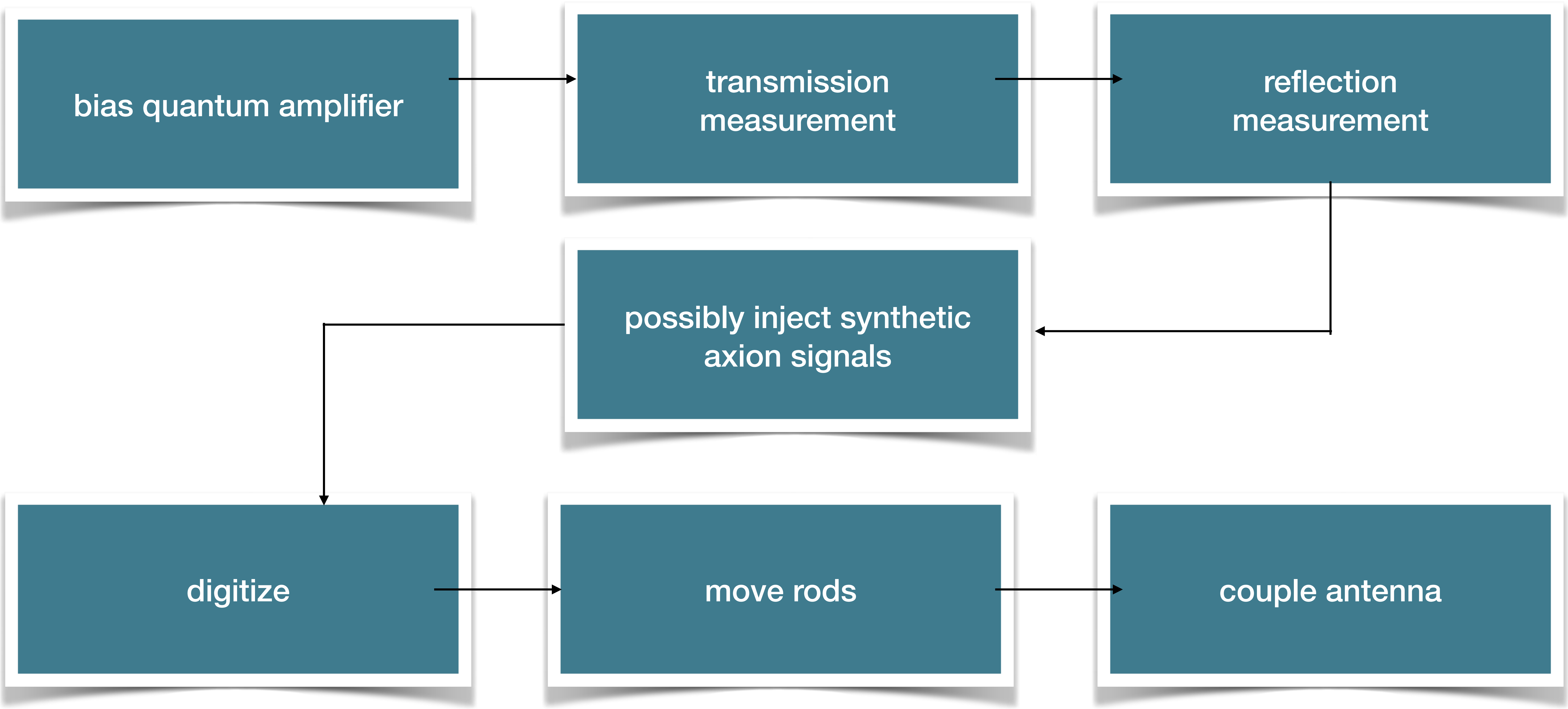
High-res

- 10 mHz native bin width
- Saved as time-series
- Non-virialized axions
- Sensitive to frequency modulation from orbital and rotational motion

Axion Doppler Shift



ADMX Run 1C data-taking?



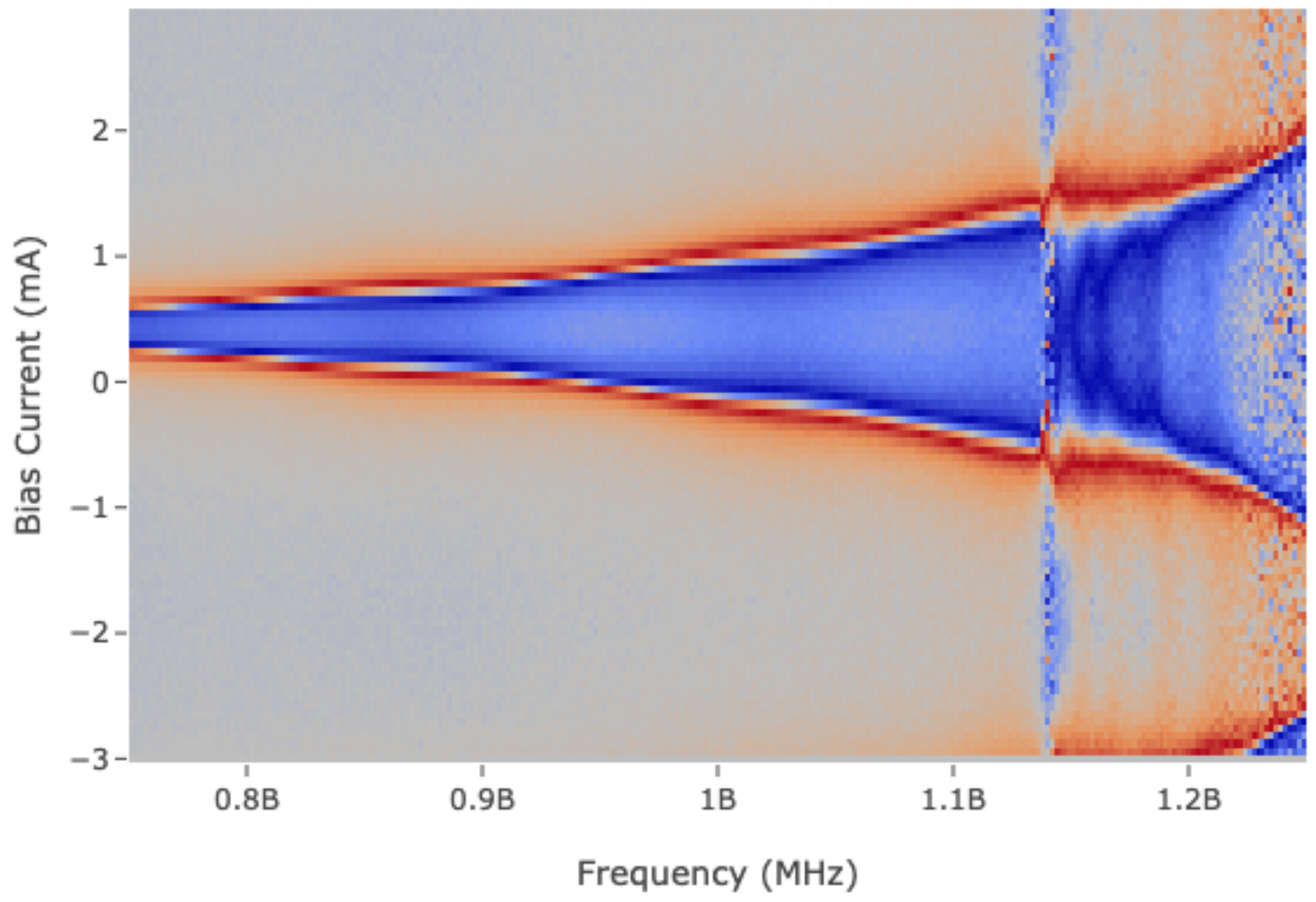
ADMX Run 1C data-taking?

bias quantum amplifier

transmission measurement

reflection measurement

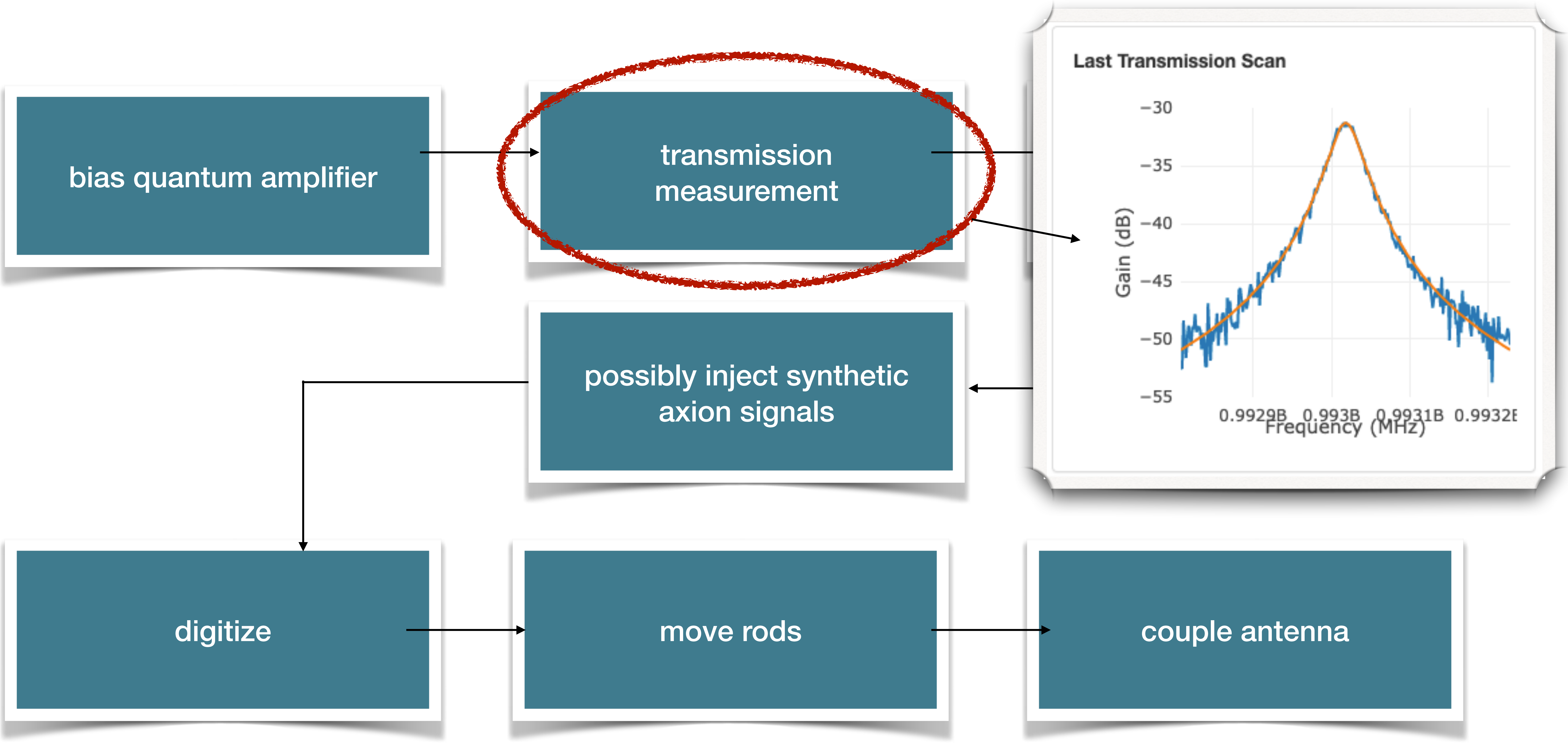
possibly inject synthetic axion signals



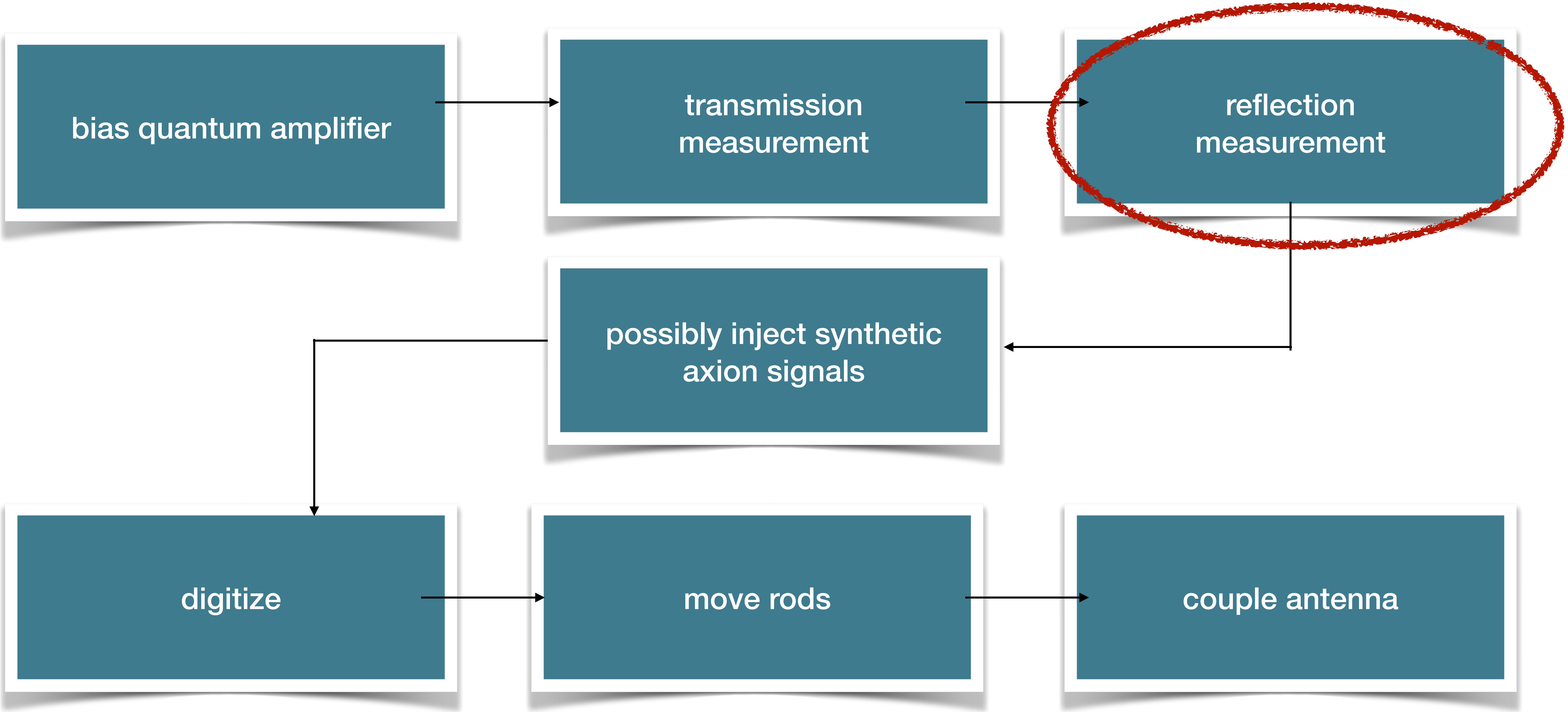
move rods

couple antenna

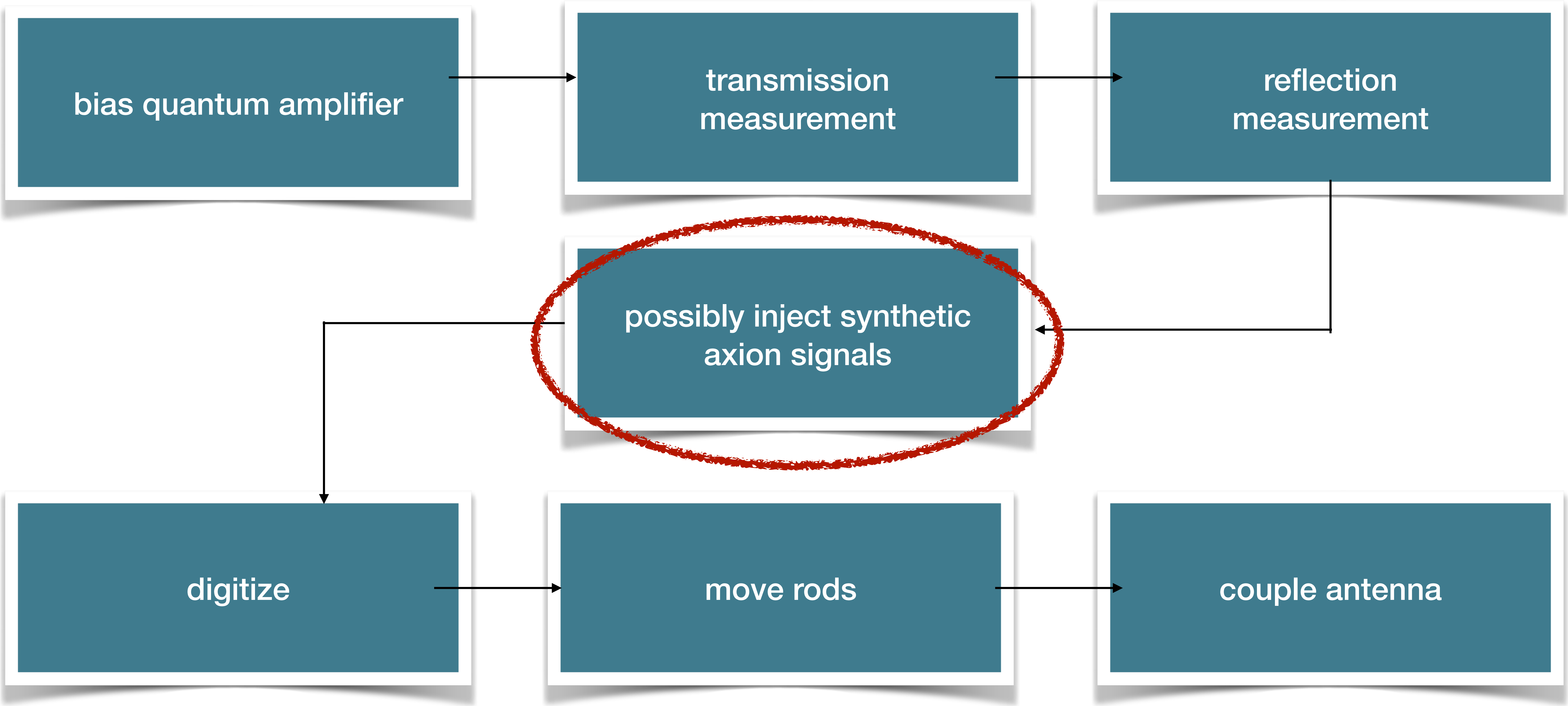
ADMX Run 1C data-taking?



ADMX Run 1C data-taking?



ADMX Run 1C data-taking?



Synthetic Axion Generator

Type 1:

Injections that we use to verify the integrity of the receiver chain and sensitivity

- Turned off in final sweep through frequency range; verified as synthetics.

- 10-12 per 10 MHz.

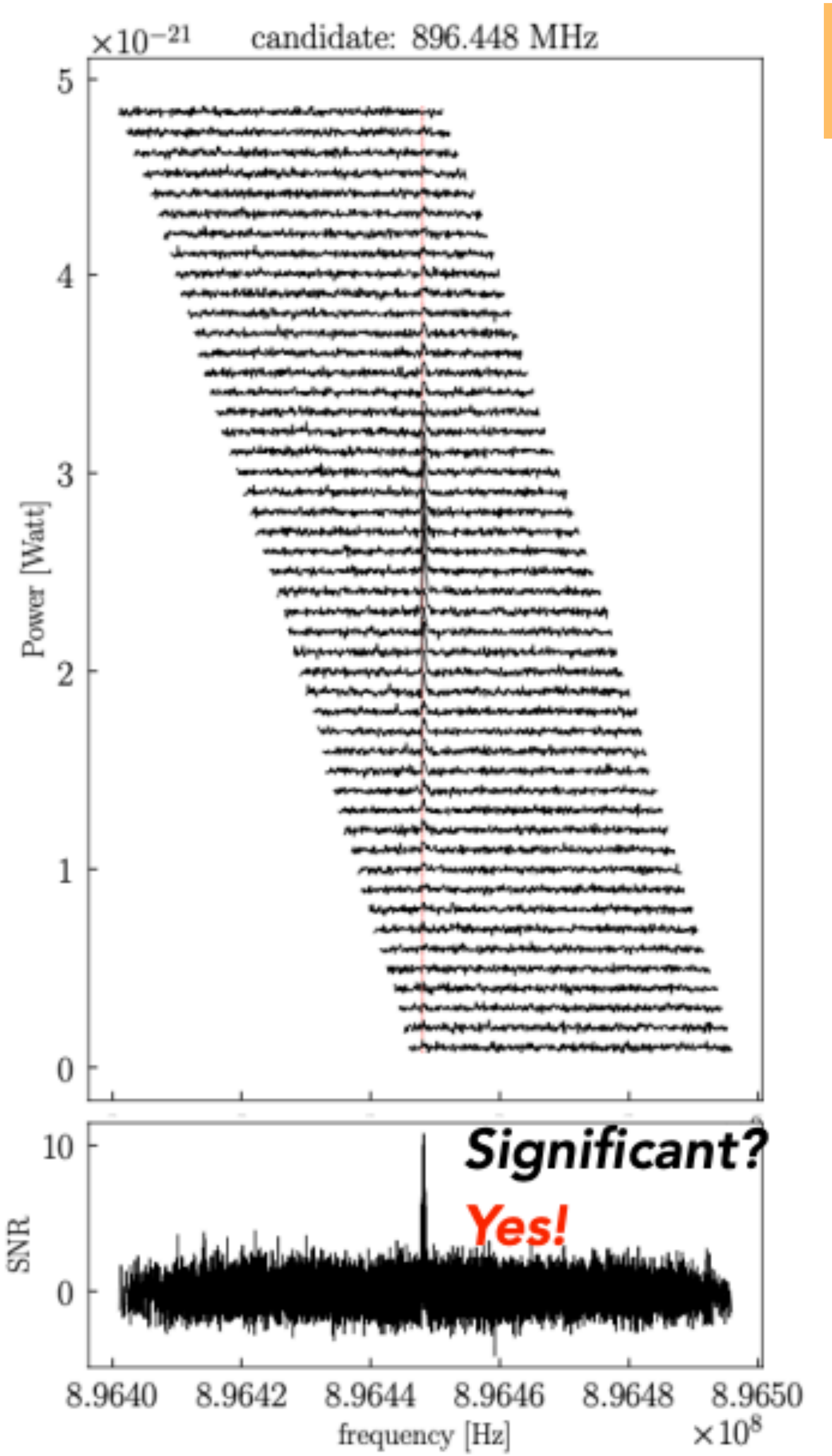
Type 2:

Injection used to practice full axion detection procedure

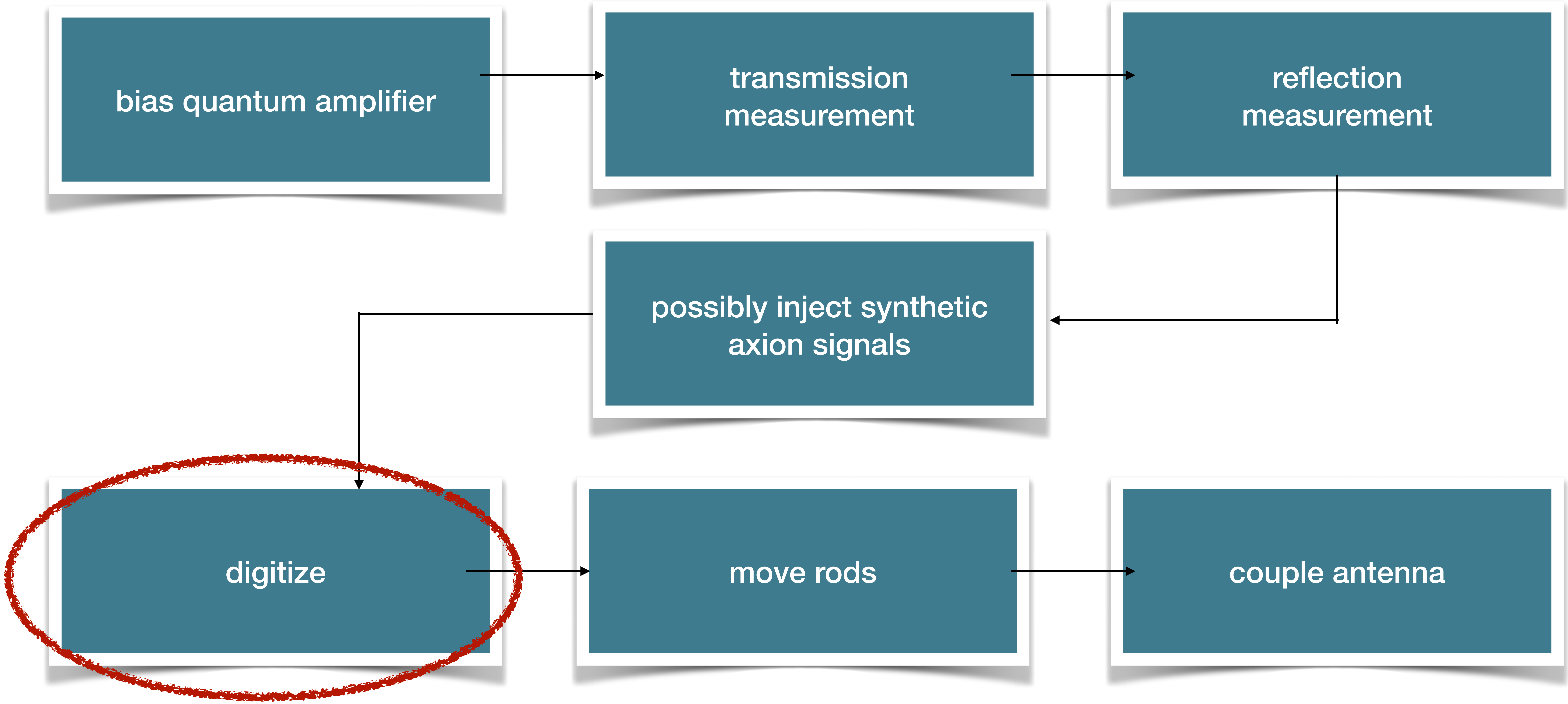
- Stay on until the ADMX operators determine that they are not real signals.

- 1-2 per run.

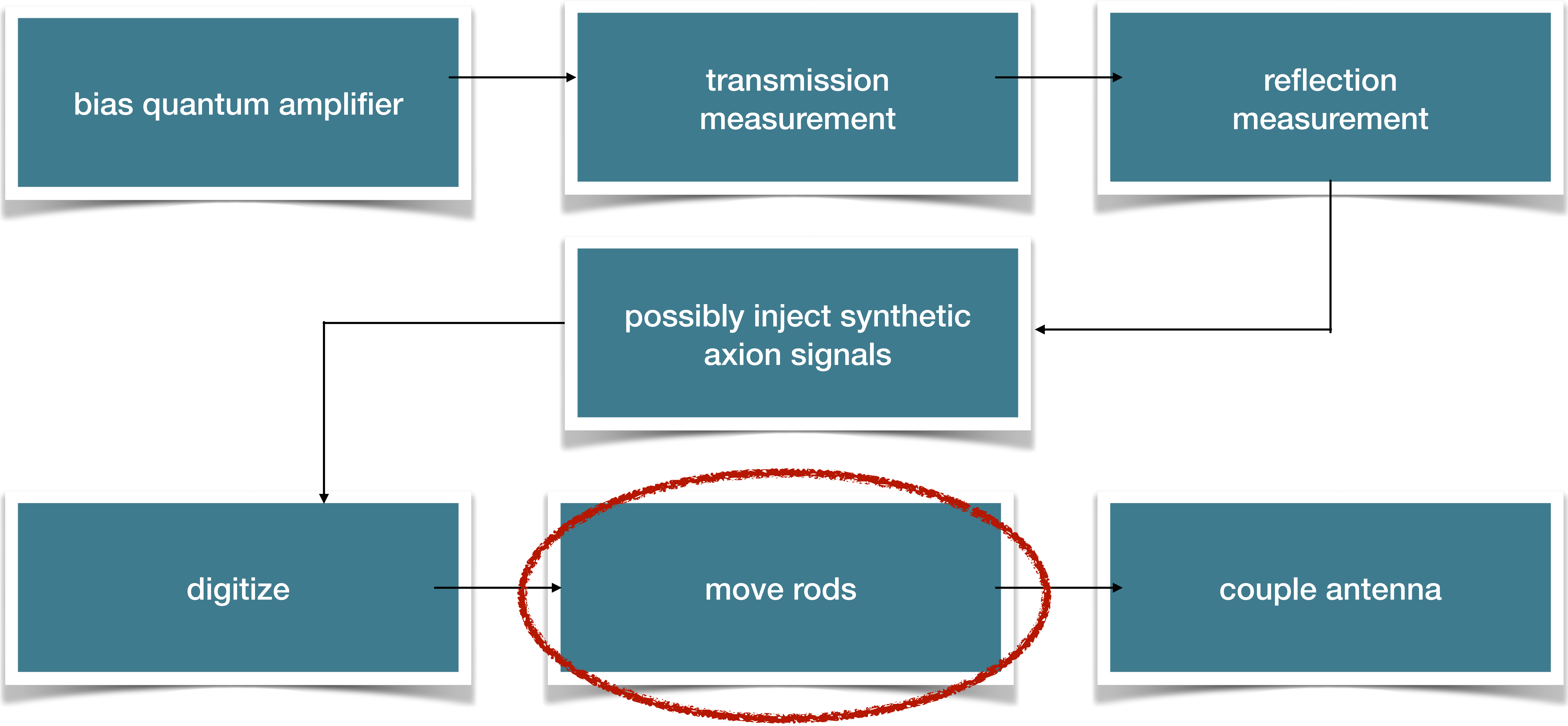
Upgrades made to Synthetic Axion Generator (SAG) for Run 1C



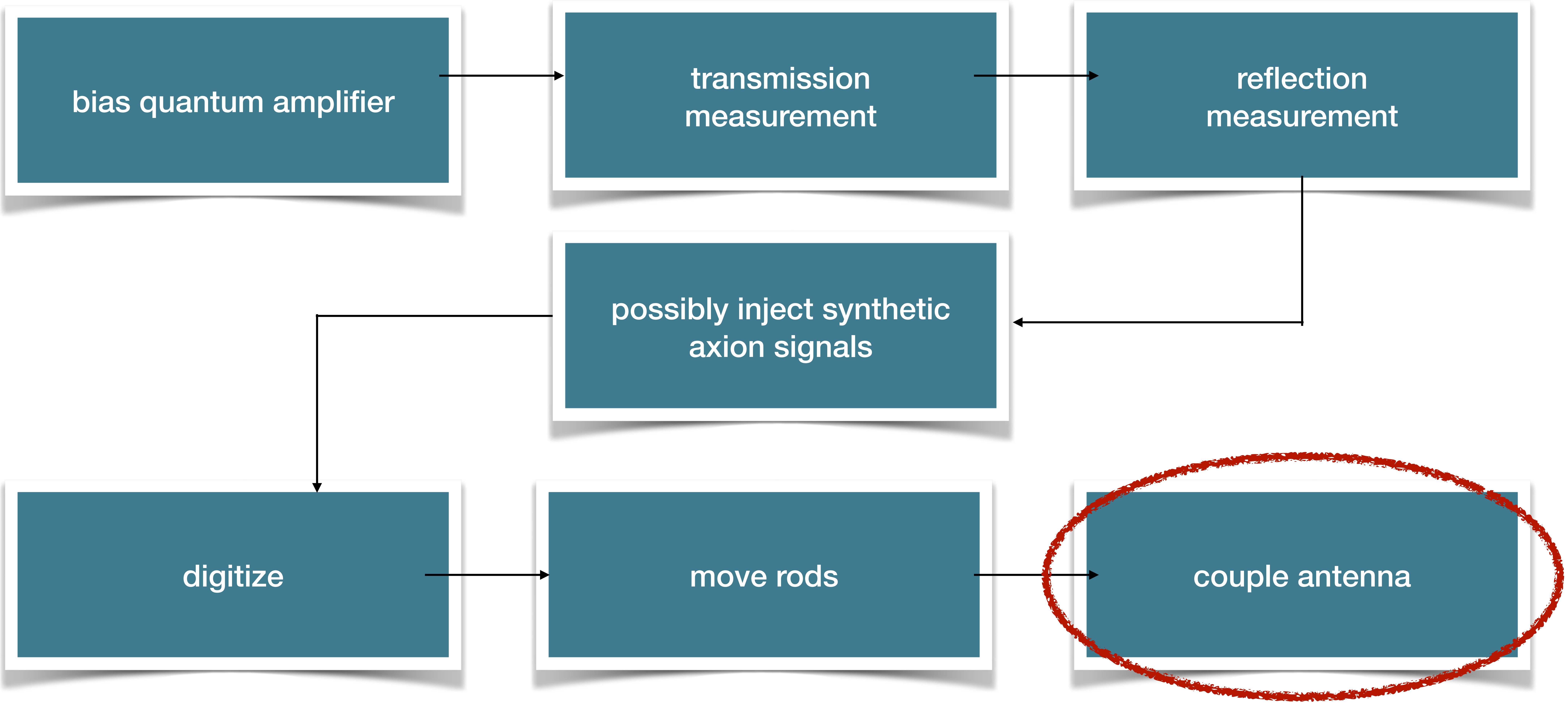
ADMX Run 1C data-taking?



ADMX Run 1C data-taking?

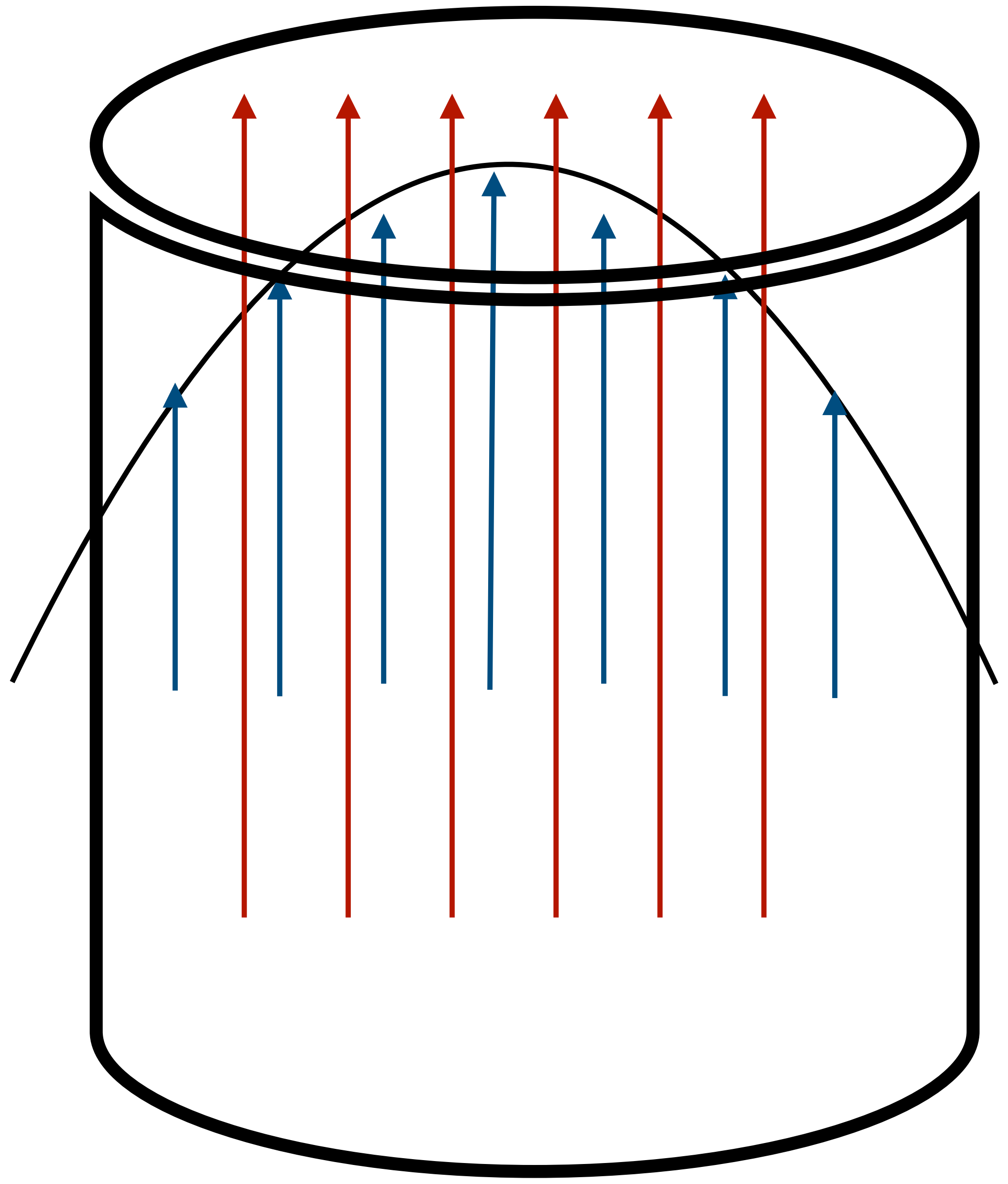


ADMX Run 1C data-taking?



Resonant Haloscope Scan Rate

$$\frac{df}{dt} \approx 543\,\frac{\text{MHz}}{\text{yr}}\left(\frac{B}{7.6\,\text{T}}\right)^4\left(\frac{V}{136\,\ell}\right)^2\left(\frac{Q_l}{30000}\right)\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{740\,\text{MHz}}\right)^2\left(\frac{\rho}{0.45\,\text{GeV/cm}^3}\right)^2\left(\frac{0.2\,\text{K}}{\text{T}_{\text{sys}}}\right)^2\left(\frac{3.5}{\text{SNR}}\right)^2$$



Red is cartoon magnetic field
Blue is cartoon axion electric field

Two factors here are inextricably linked…

Small volume

Smaller wavelength of TM010 mode

Higher frequency (mass) of axion you can detect

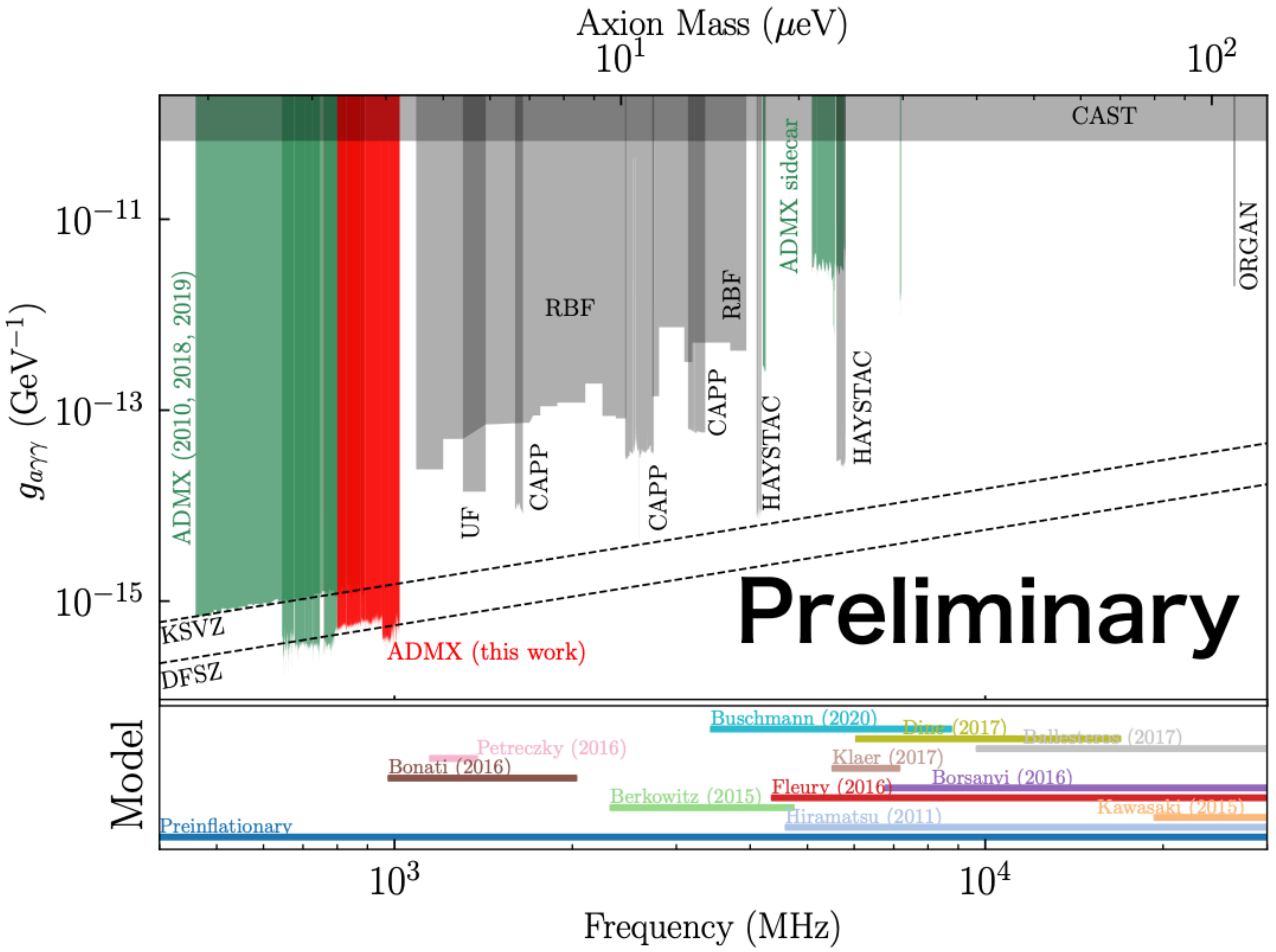
$$C_{010} = \frac{|\int dV\, \vec{B}_{ext} \cdot \vec{E}_a|^2}{B_{ext}^2 \int dV\, \epsilon_r |\vec{E}_a|^2}$$

"Form Factor"

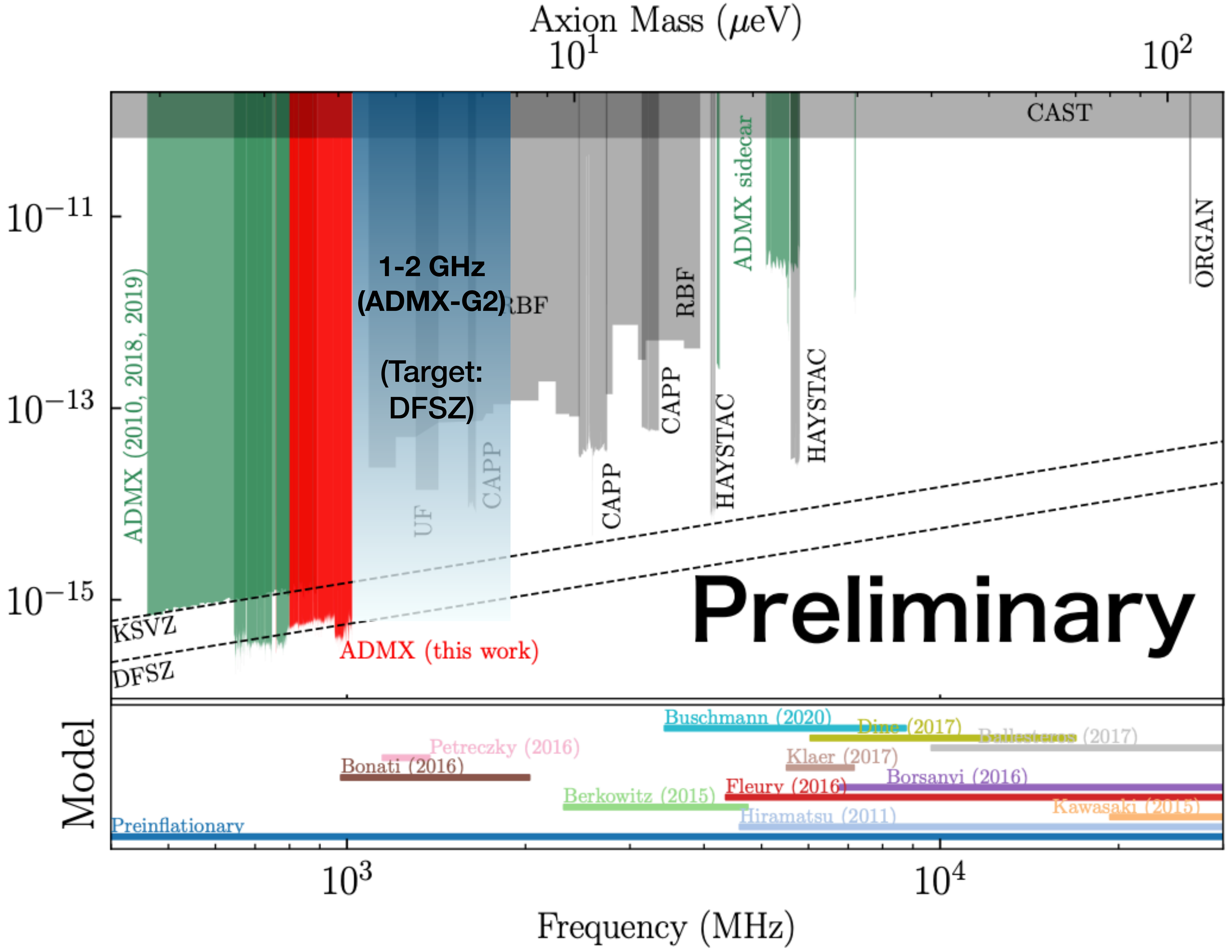
Axion scaling challenge?

Higher Frequencies → Smaller Volumes → Slower Scan Rate

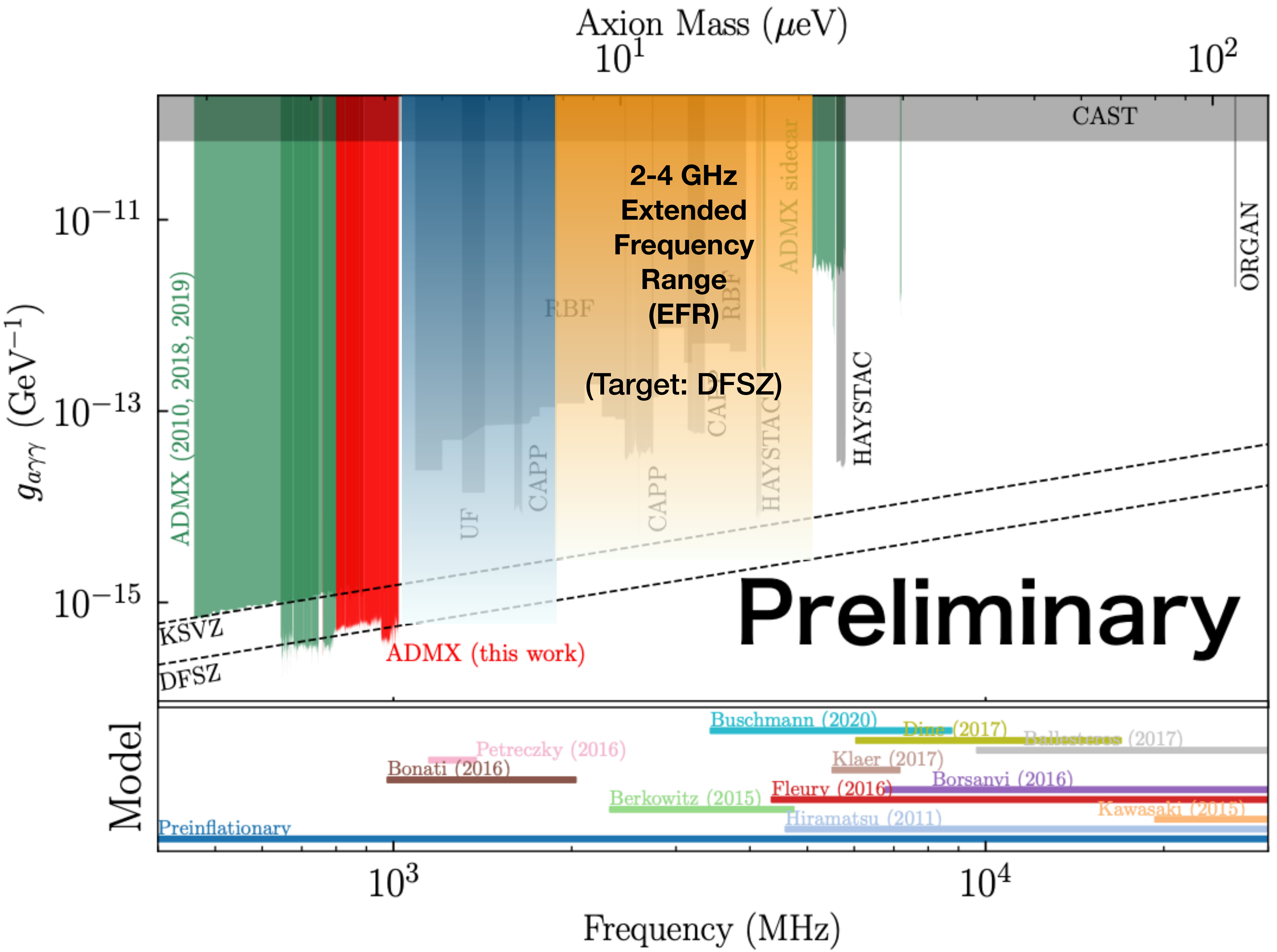
Where do we go from here?



Axion Mass (μeV)
10^1
10^2
CAST
ADMX sidecar
ORGAN
10^-11
10^-13
10^-15
g_aγγ (GeV^-1)
ADMX (2010, 2018, 2019)
RBF
RBF
UF
CAPP
CAPP
CAPP
HAYSTAC
HAYSTAC
KSVZ
DFSZ
ADMX (this work)
Preliminary
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

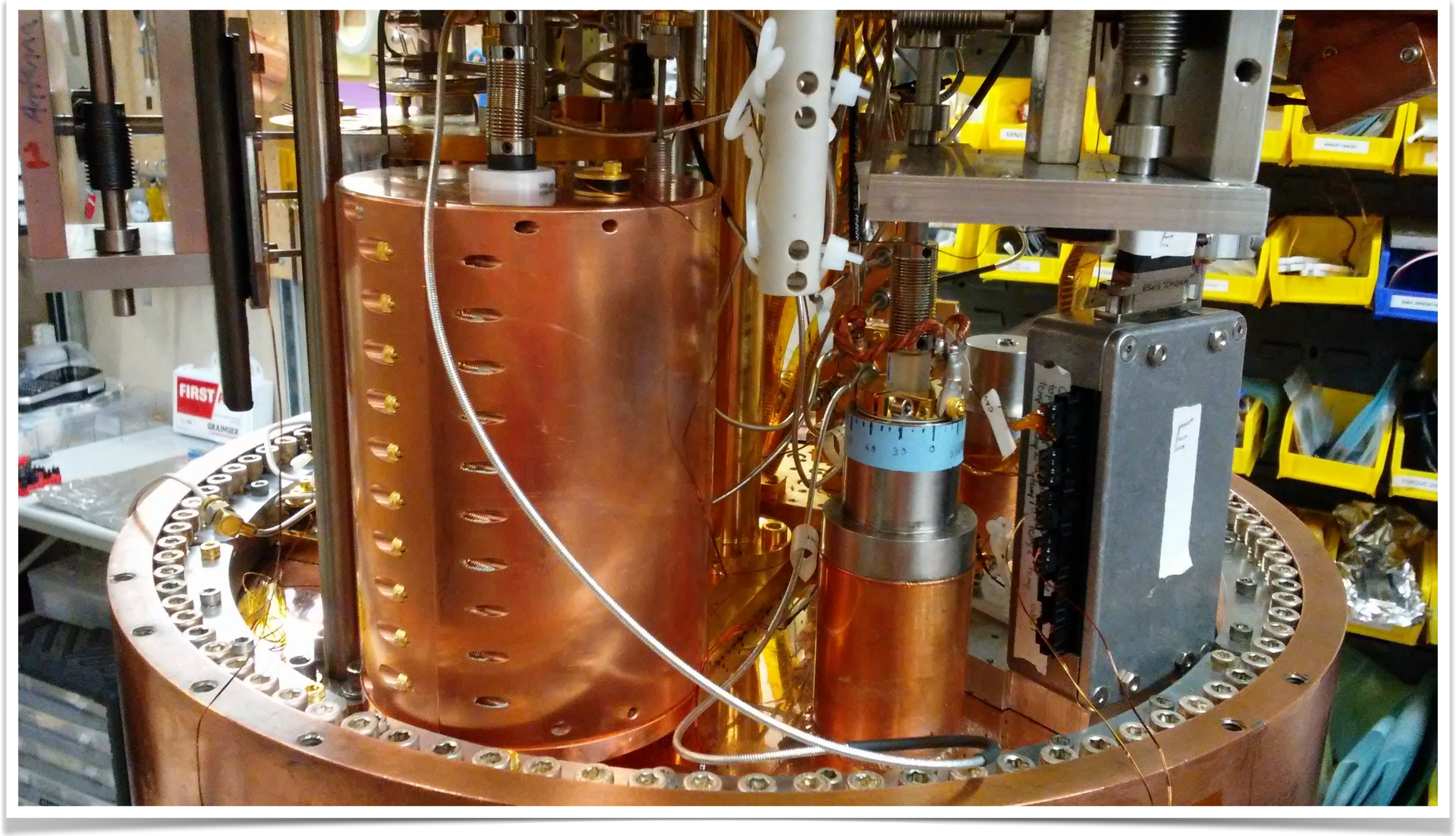


Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
$g_{a\gamma\gamma}$ (GeV^{-1})
10^−11
10^−13
10^−15
ADMX (2010, 2018, 2019)
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
RBF
RBF
UF
CAPP
CAPP
CAPP
HAYSTAC
HAYSTAC
ADMX sidecar
KSVZ
DFSZ
ADMX (this work)
Preliminary
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Berkowitz (2015)
Fleury (2016)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)


Axion Mass (μeV)
10^1
10^2
CAST
2-4 GHz
Extended
Frequency
Range
(EFR)
(Target: DFSZ)
ADMX sidecar
RBF
RBF
CAPP
CAPP
CAPP
UF
HAYSTAC
HAYSTAC
ORGAN
ADMX (2010, 2018, 2019)
KSVZ
DFSZ
ADMX (this work)
Preliminary
10^-11
10^-13
10^-15
g_aγγ (GeV^-1)
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Berkowitz (2015)
Fleury (2016)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

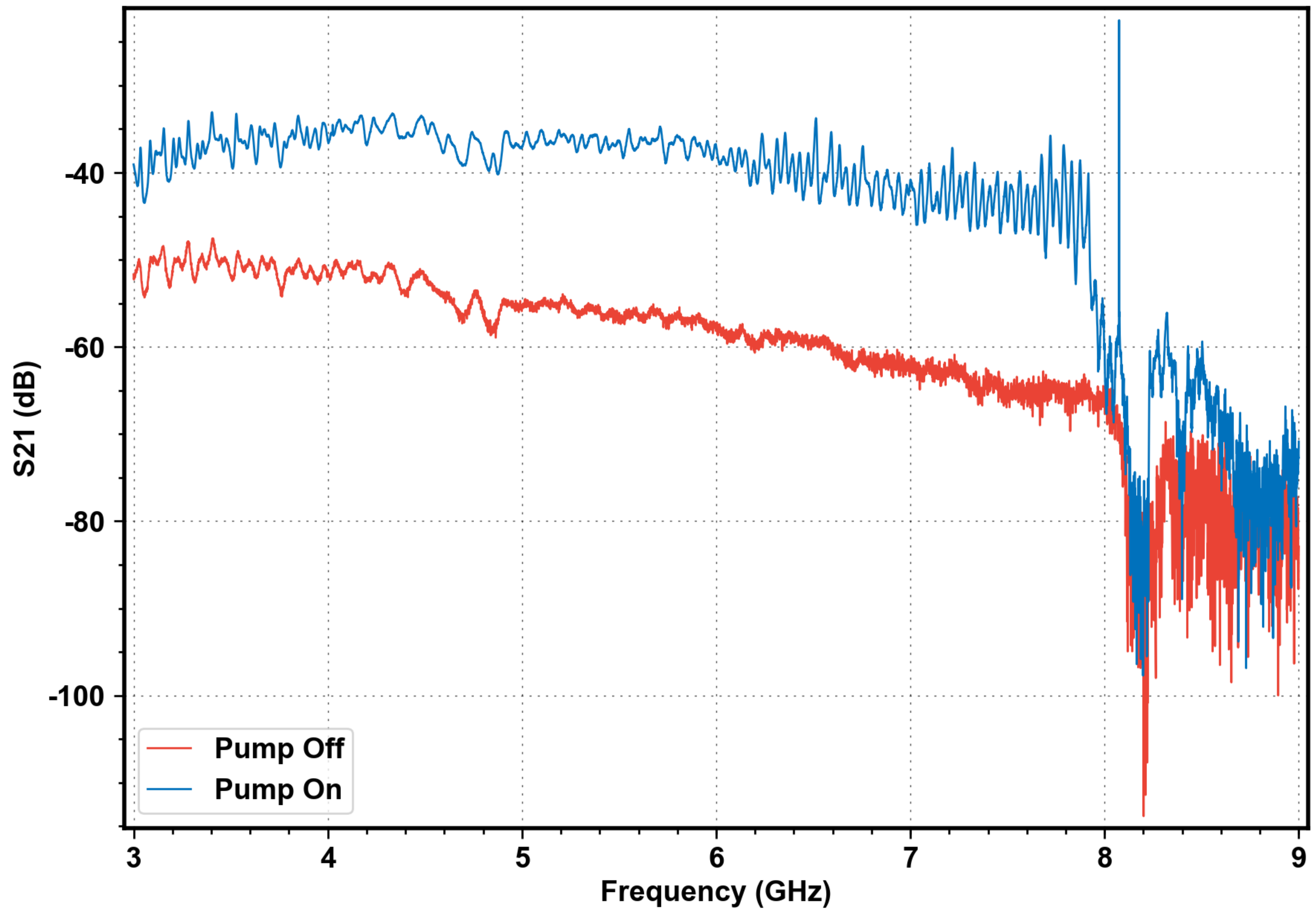
Sidecar Experiment

- Sidecar is a small prototyping cavity that sits on top of the main cavity.
- This iteration of sidecar is testing:
  - Traveling Wave Parametric Amplifier (TWPA)
  - Clamshell cavity design
  - Piezo motors for antenna and tuning rod

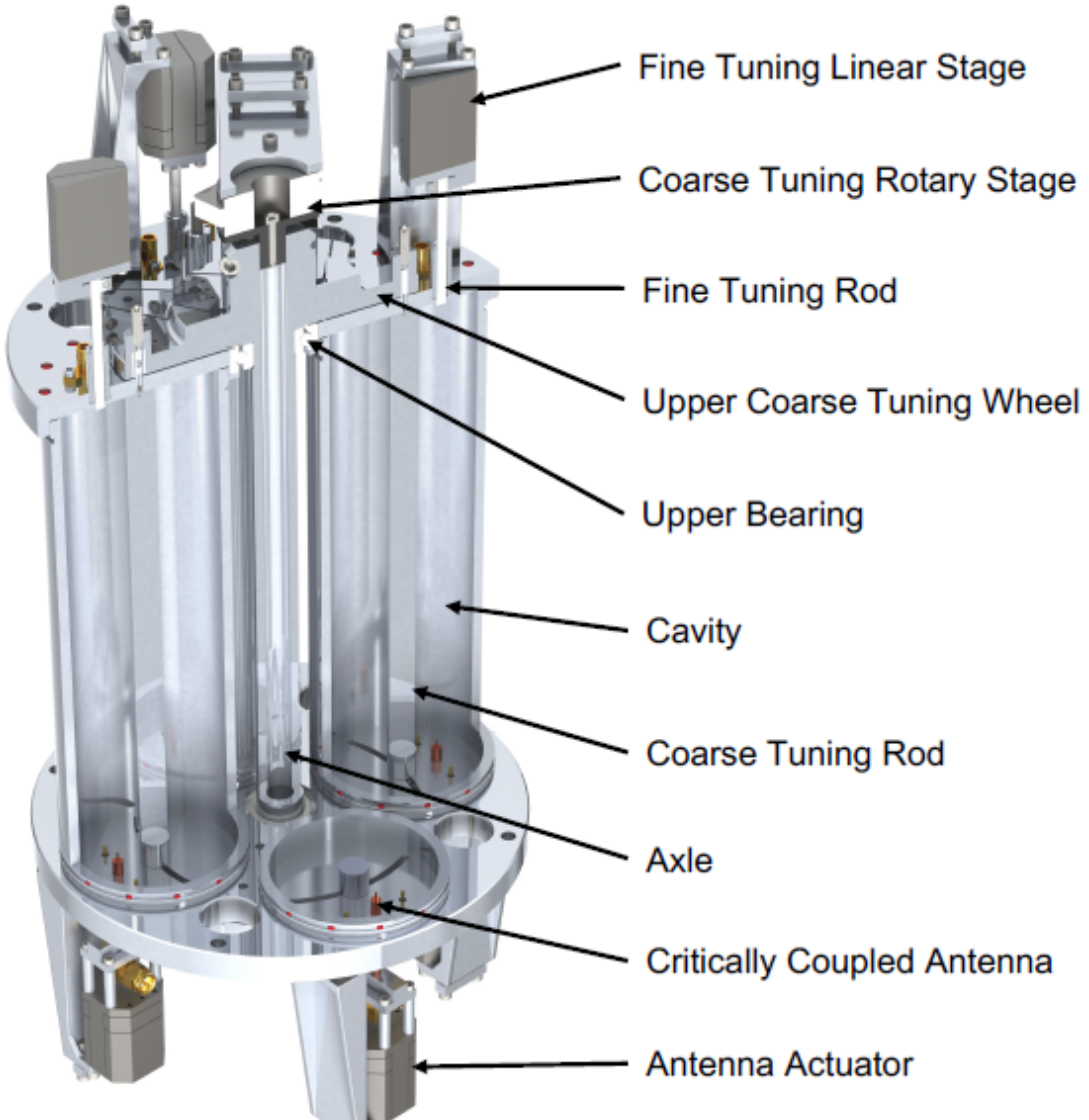


Traveling Wave Parametric Amplifier

- Benefits of TWPA include
  - Broadband gain spans several GHz.
  - Eliminates need for an additional circulator (Less loss, more space)
  - Reasonable noise performance
- ADMX Sidecar Demonstration
  - Operated TWPA for several weeks in magnetic field
  - Reasonable performance (achieved ~8 dB SNR)



Multi-cavity arrays

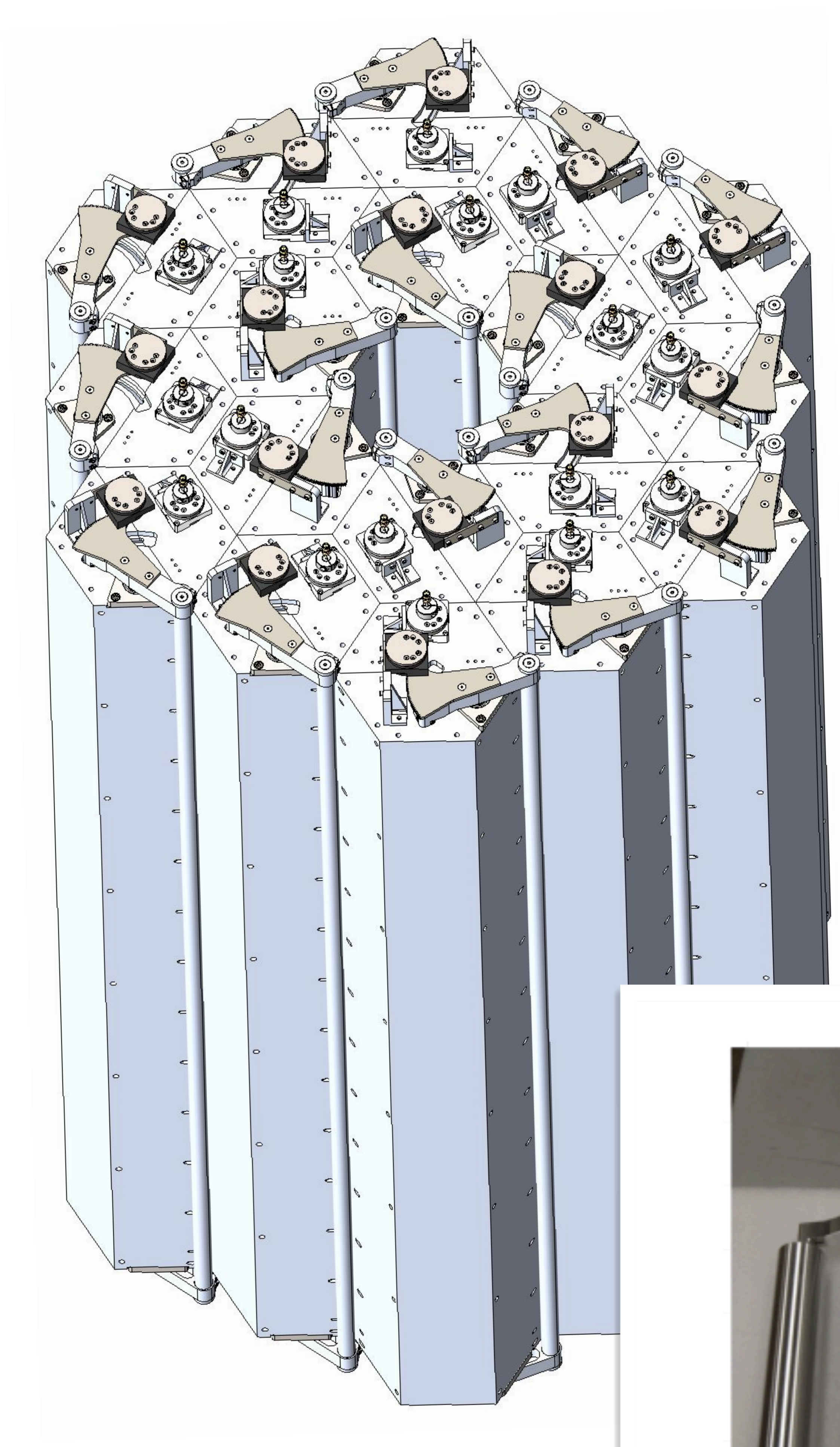


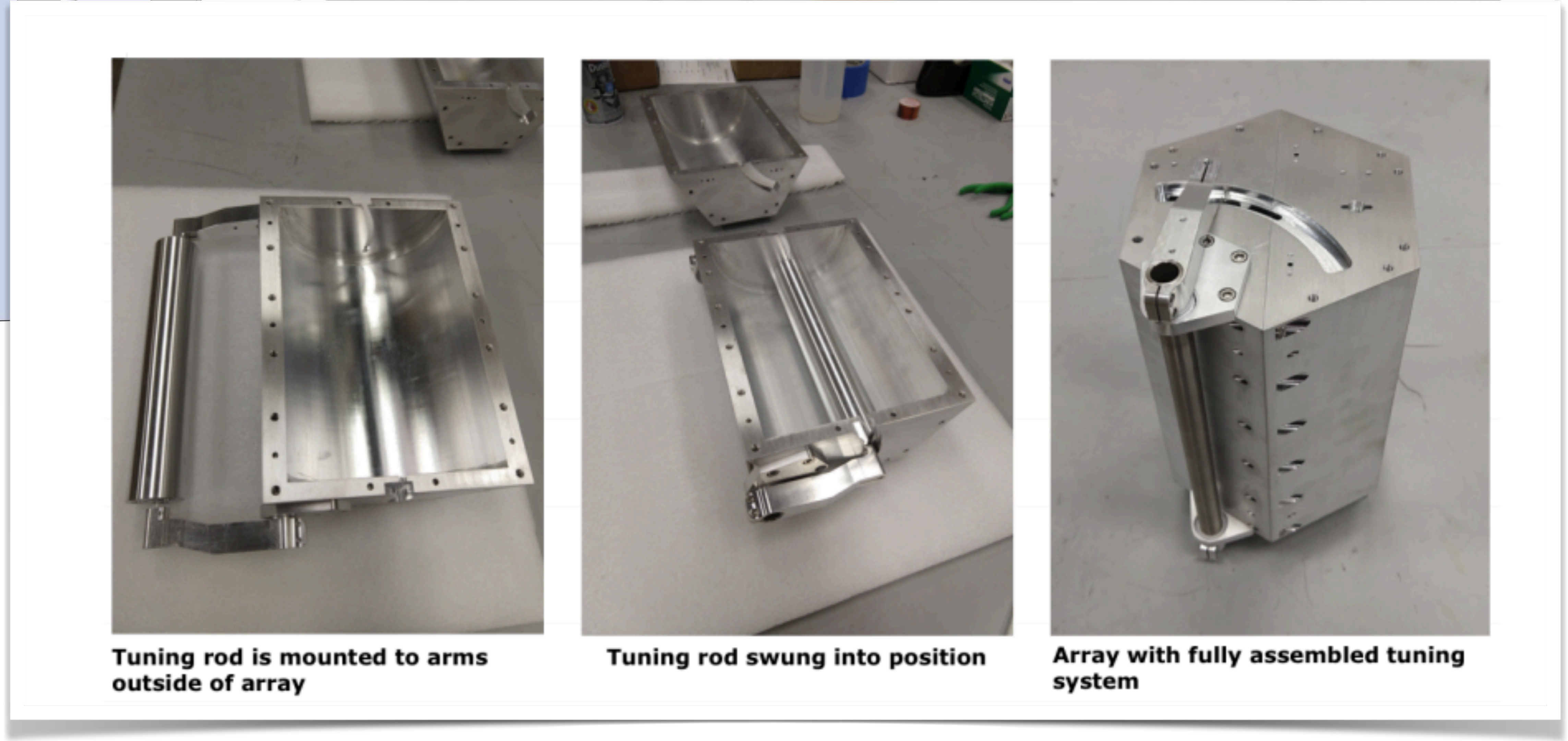
4-cavity array planned for University of Washington

- 1.4-2.2 GHz
- Amplitude-combine cavities in phase for improved SNR.
- Scan rate ~ $(N)^2$: N cavities in phase allows factor of N increase in scan rate relative to power combining after the fact
- Setup has common rotor with coarse tuning rods.
- Fine-tuning done by perturbing fields with sapphire mounted to linear stage.

ADMX Extended Frequency Range

- Scan rate goes as B^4 = High field critical for future axion searches.
- Scan rate goes as V^2 = Large volume critical for future axion searches.
- ADMX Collaboration plans to use large-bore 9.4 T magnet currently at UIUC.
- Room for R&D work in this magnet as well!

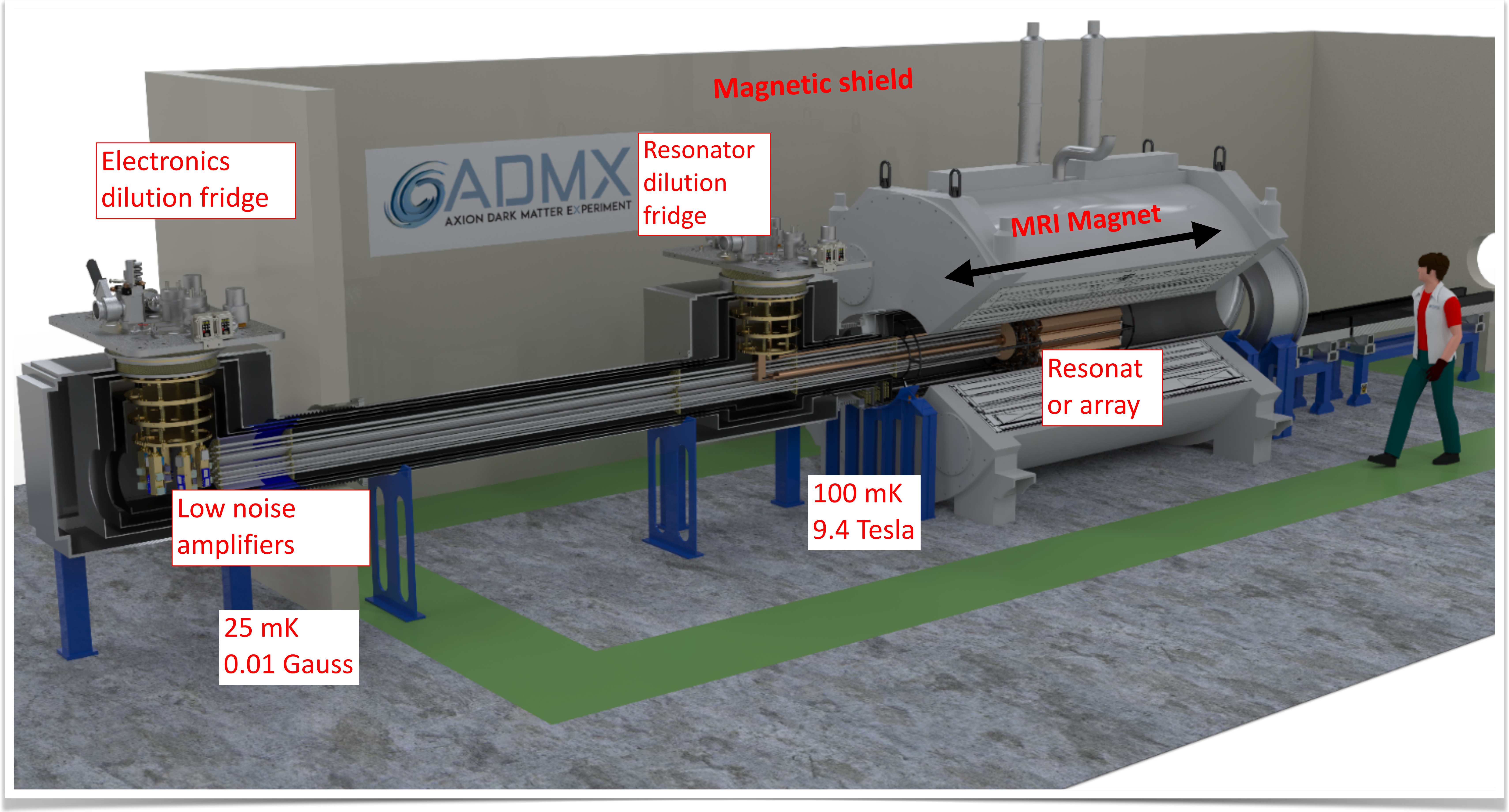




ADMX Extended Frequency Range

New Features

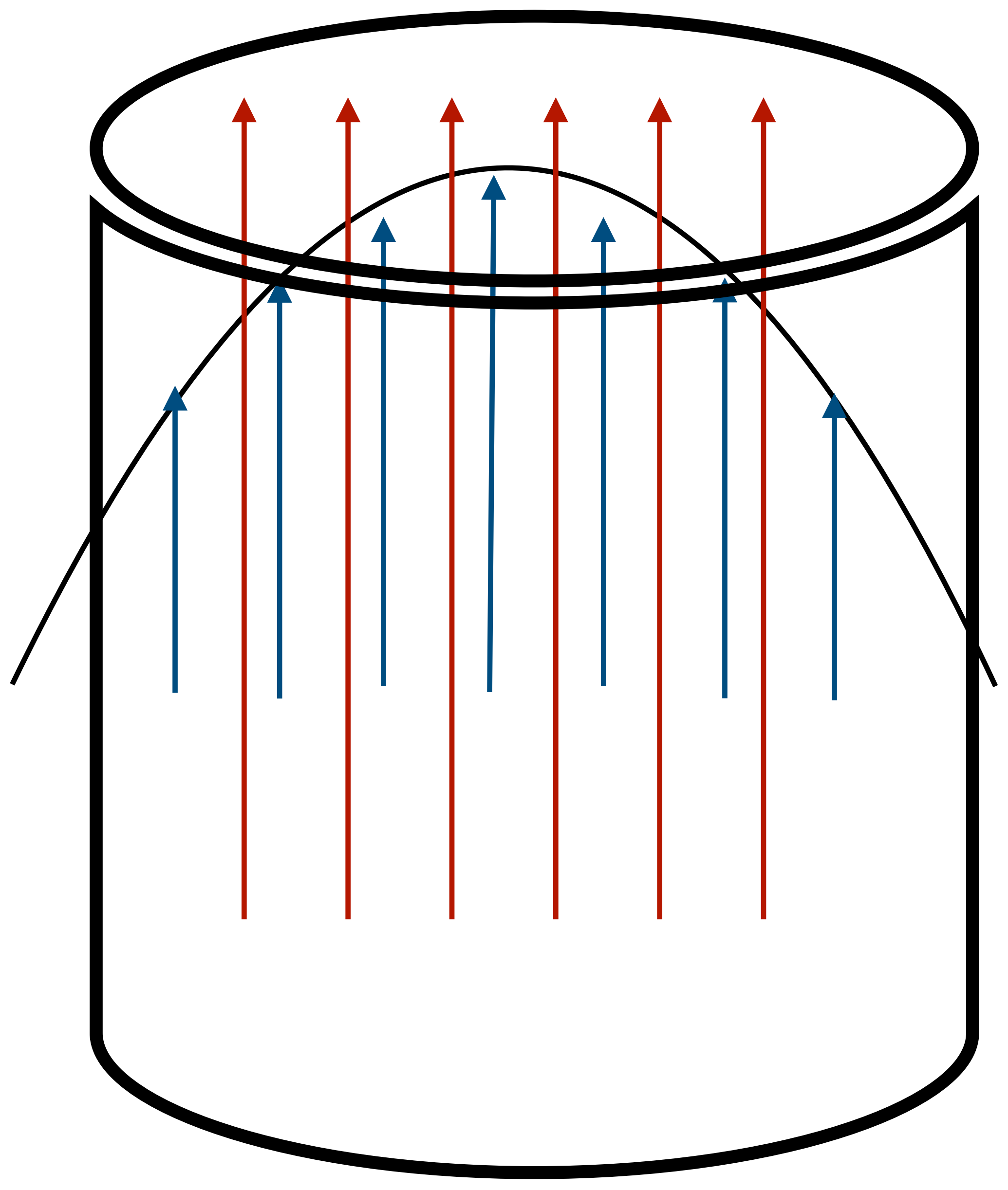
- Horizontal magnet bore
- Extra modularity: cavity electronics are separate from magnet bore
- Large magnet volume: 258 liters
- Preferred site for ADMX-EFR: PW8 Hall at Fermilab
- Other: Squeezing? Superconducting cavities?



(ADMX EFR Design)

Resonant Haloscope Scan Rate

$$\frac{df}{dt} \approx 543\,\frac{\mathrm{MHz}}{\mathrm{yr}}\left(\frac{B}{7.6\,\mathrm{T}}\right)^4\left(\frac{V}{136\,\ell}\right)^2\left(\frac{Q_l}{30000}\right)\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{740\,\mathrm{MHz}}\right)^2\left(\frac{\rho}{0.45\,\mathrm{GeV/cm^3}}\right)^2\left(\frac{0.2\,\mathrm{K}}{\mathrm{T_{sys}}}\right)^2\left(\frac{3.5}{\mathrm{SNR}}\right)^2$$



Red is cartoon magnetic field
Blue is cartoon axion electric field

Two factors here are inextricably linked…

Small volume

Smaller wavelength of TM010 mode

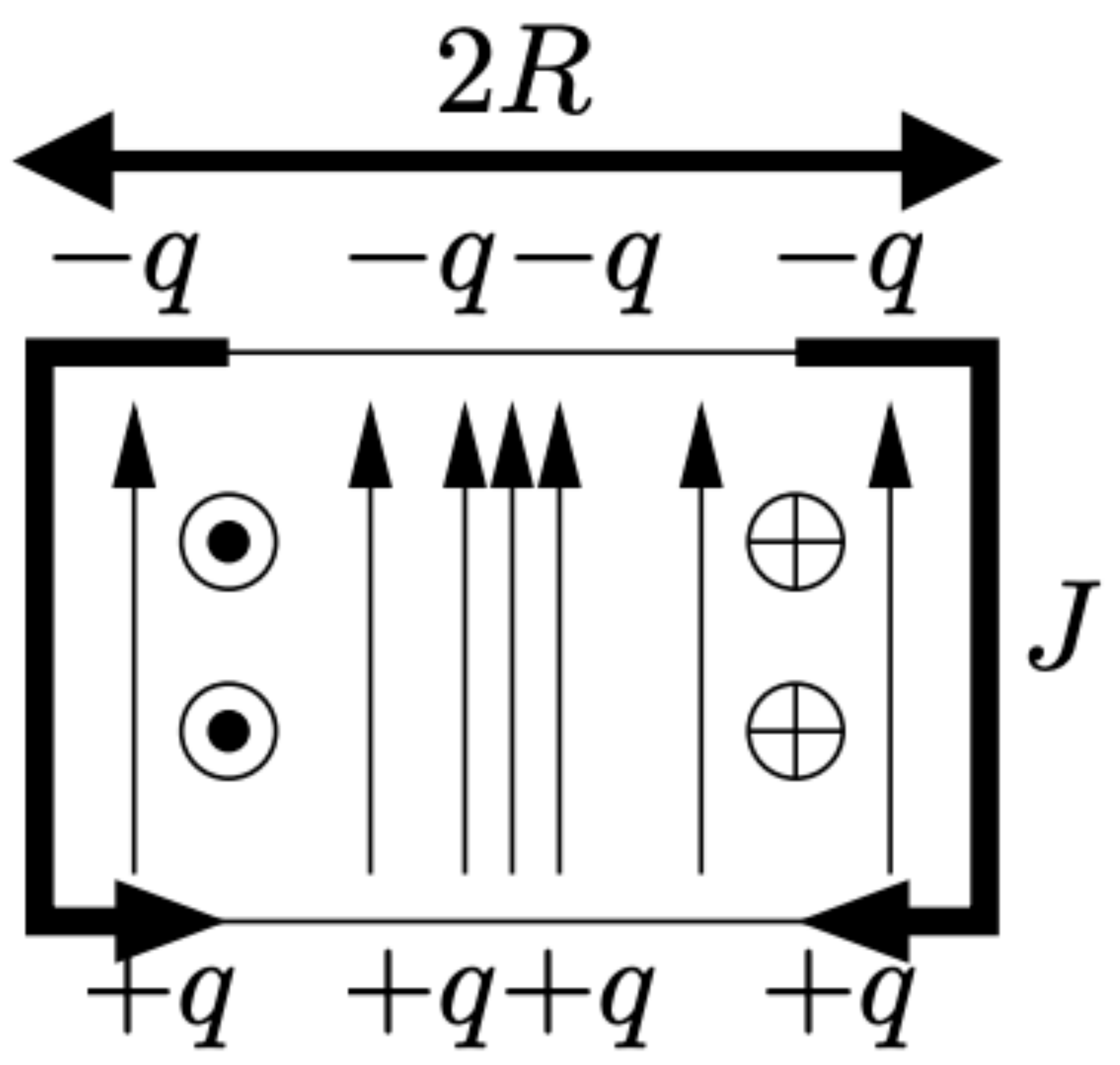
Higher frequency (mass) of axion you can detect

$$C_{010} = \frac{|\int dV\,\vec{B_{ext}}\cdot\vec{E_a}|^2}{B_{ext}^2\int dV\,\epsilon_r|\vec{E_a}|^2}$$

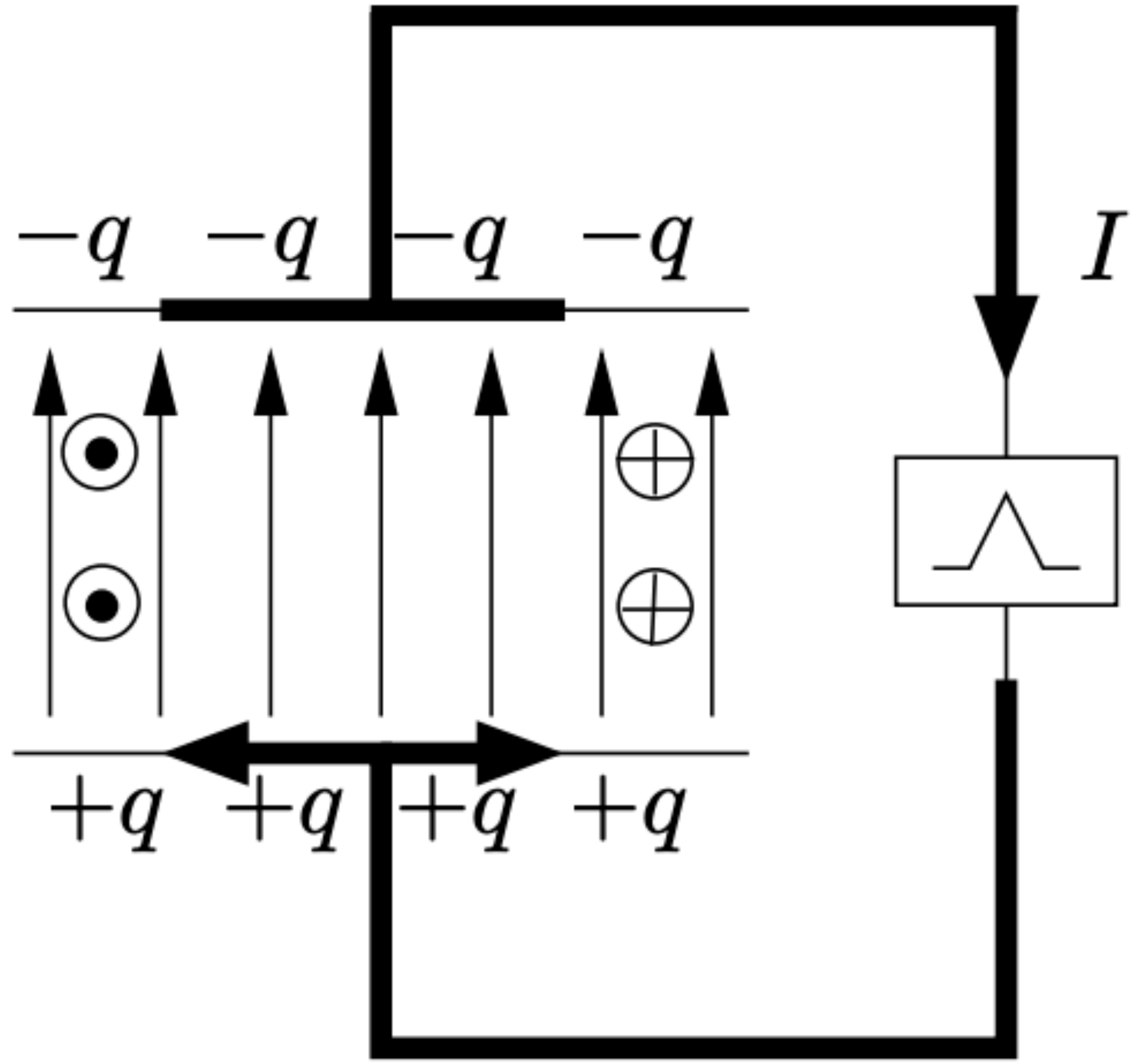
“Form Factor”

Resonant Feedback Concept

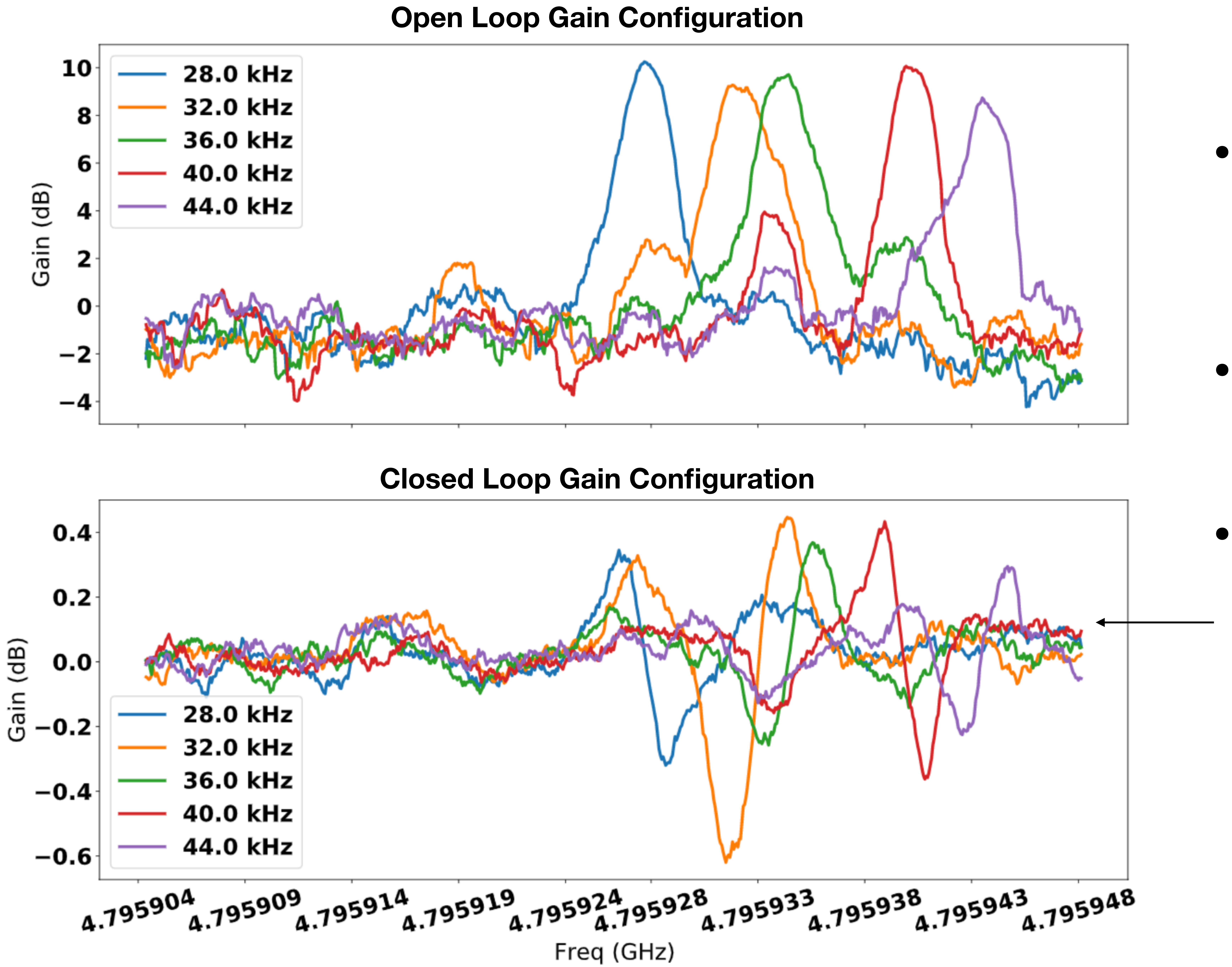
Cavity



Resonant feedback



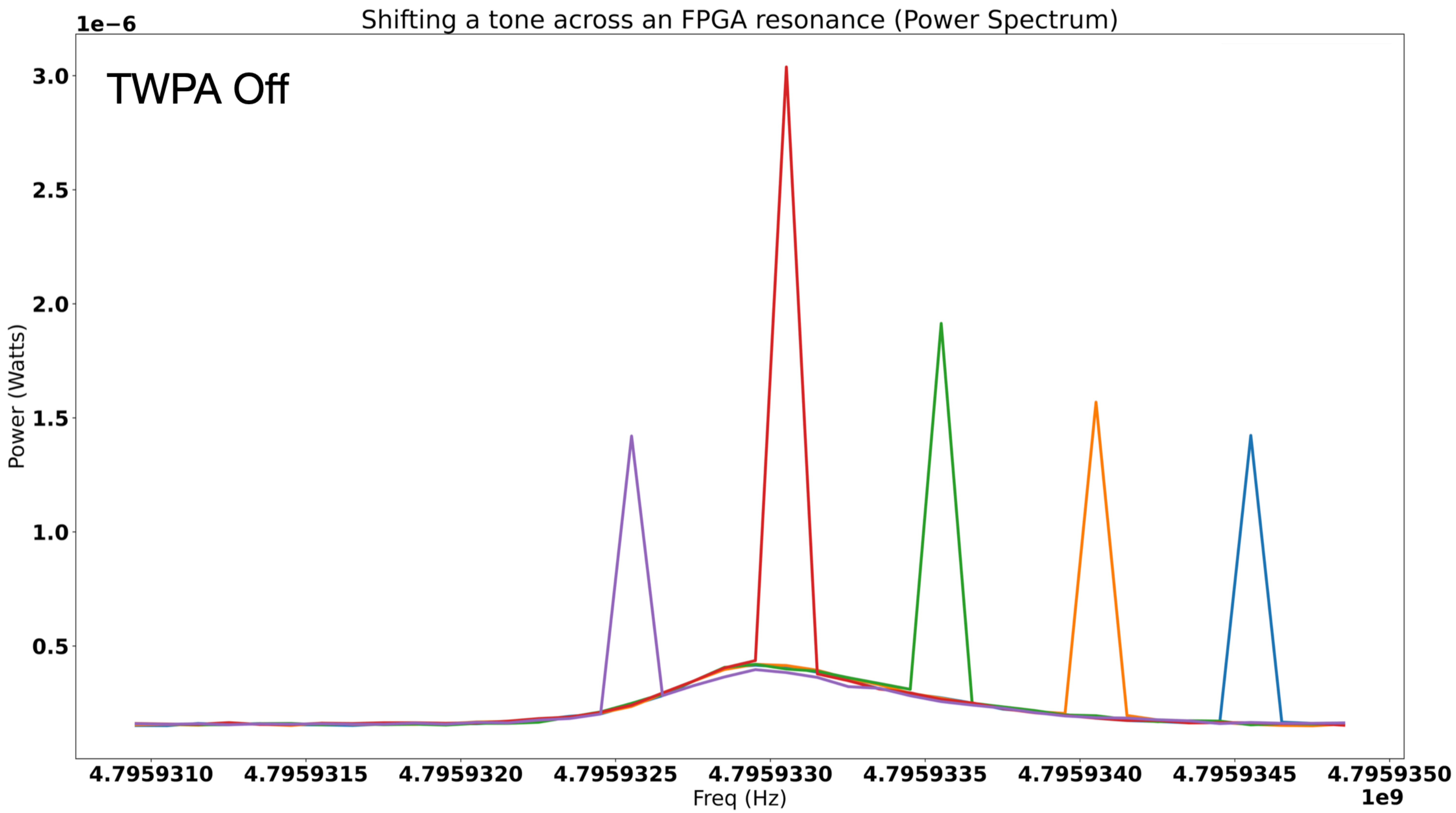
Nuclear Inst. and Methods in Physics Research, A, Volume 921, p. 50-56.
https://arxiv.org/abs/1805.11523



- Generated resonances on the FPGA board.
- Shape from FPGA filter is Lorentzian.
- Can see resonances in a VNA measurement across the cavity.

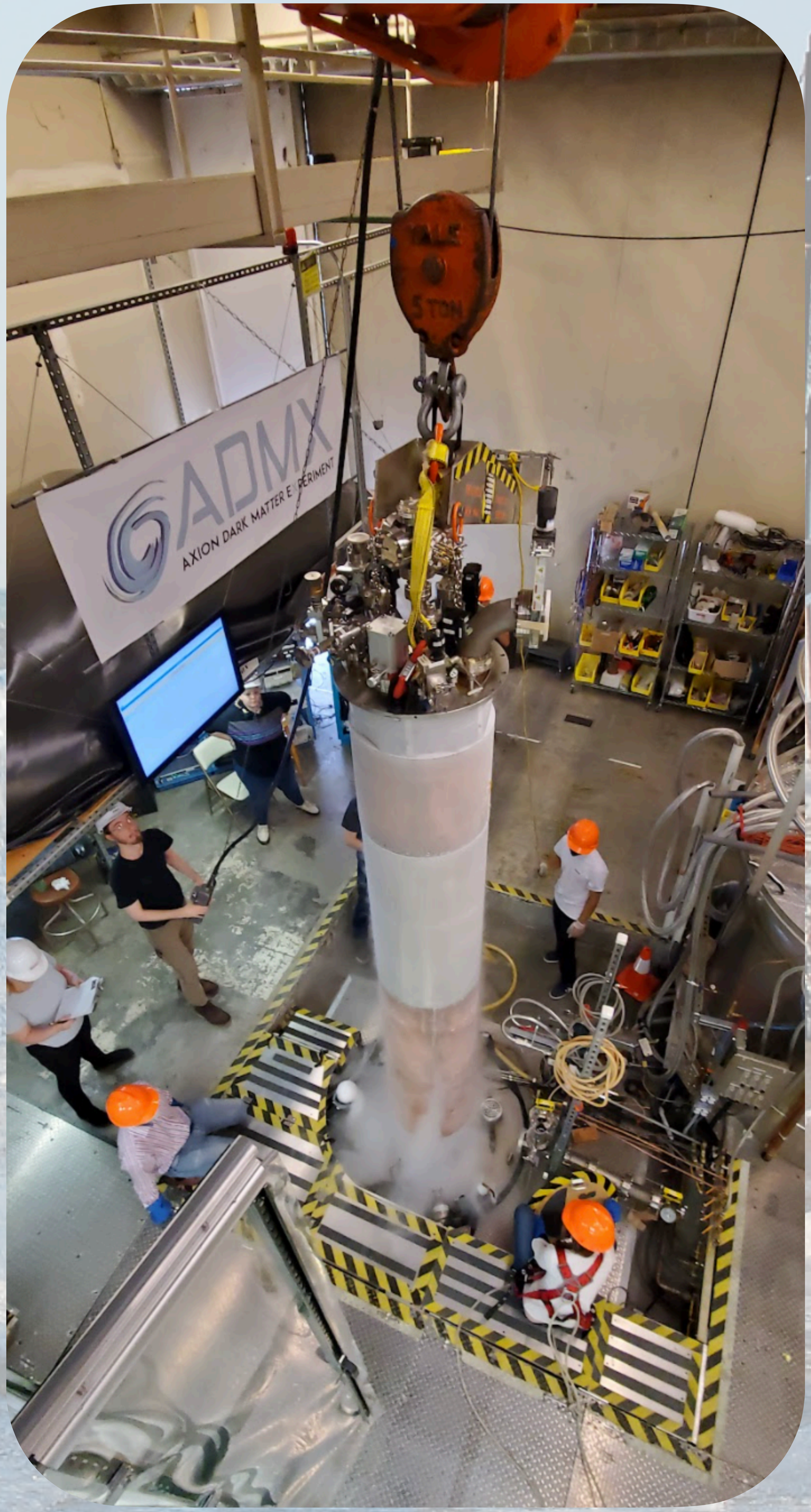
Resonant Feedback Concept

- The injected tone is enhanced when on resonance, and diminished when off resonance.
- Behaves like cavity resonance.
- Further studies to ensue (noise studies, feedback controls).



Conclusions

- ADMX has completed the first half of Run 1C data-taking
- Will resume second half at DFSZ sensitivity after upgrades
- First implementation of a TWPA in a dark matter axion search
- Progress is being made towards higher frequency searches
- Discovery could happen at any moment.



Acknowledgements

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.